Cosmological Insights from Gravitational Lensing – or: how Herr Doktor Einstein Can Come to the Rescue and Help Us Solve the Grandest Mystery in Modern-Day Physics

Talk to the Night Sky Network regular meeting
(arranged by Dr. David Prosper)
Th Sept 25 2014

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SLAC National Accelerator Laboratory (SLAC NAL), Stanford, CA.

For more info, see also “Extra Cosmo Resources” link near top of:

Mandeep.Org

And if you like the talk feel free to “Like” it and/or ask more questions directly at:

https://www.facebook.com/MSSGTalks

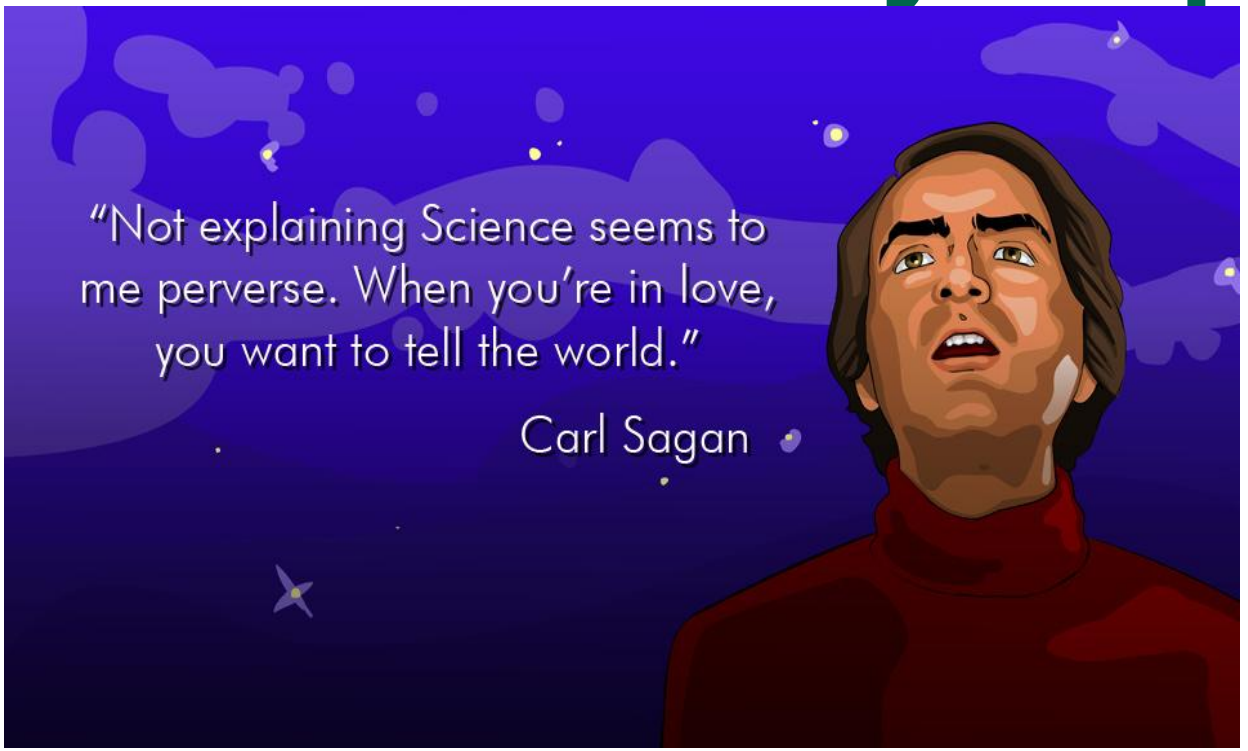
For more information/further questions : ***me@mandeep.org***

(Also listed at the bottom of *mandeep.org)*

Talk Plan

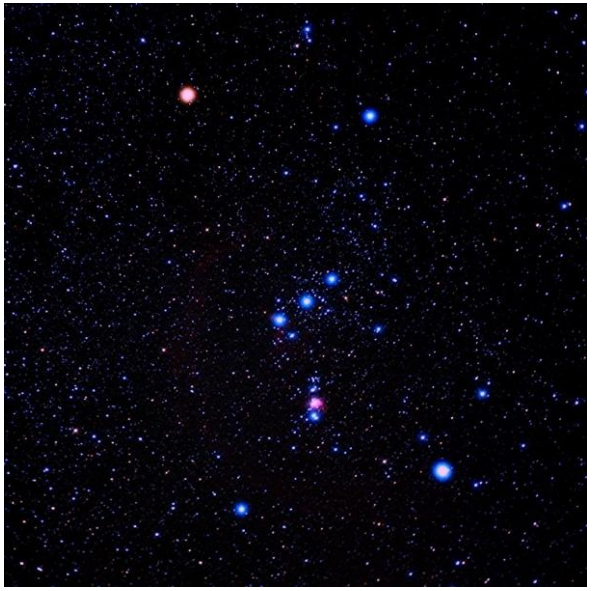
- The connections of the smallest with the largest
- “Dark Matter” - DM
- “Dark Energy” - DE
- Bring all this back to Earth for a minute
- Introducing gravitational lensing
- How lensing can help us with DM and DE determination
- The future is bright in this field!

Some of My Inspirations

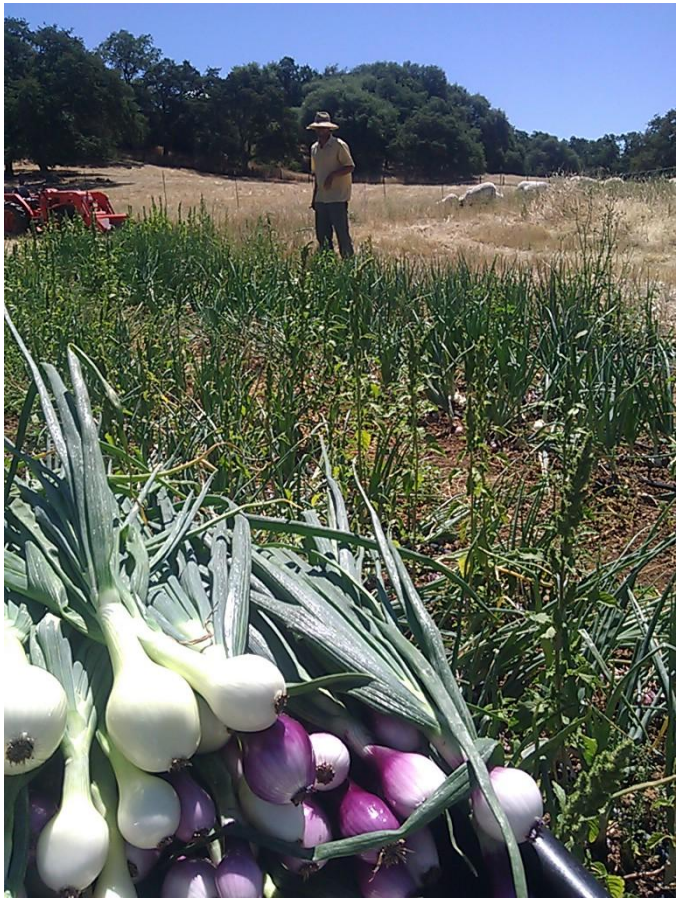


Great awe-filled scientists of the past

Looking up at the Night Sky



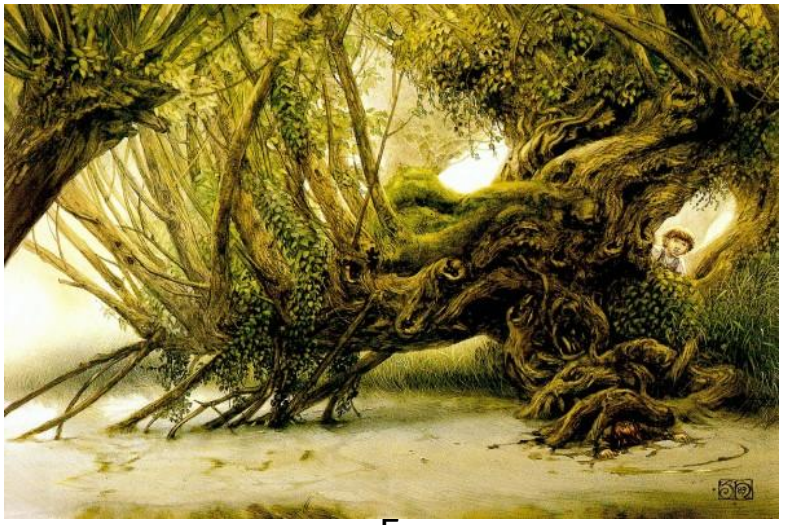
Being in Nature



One thing to take away

After evolving separately for decades, particle physics and cosmology have strongly reconverged

Essentially and what the Universe is made of, and how it came to be, are inextricably linked ideas at root.



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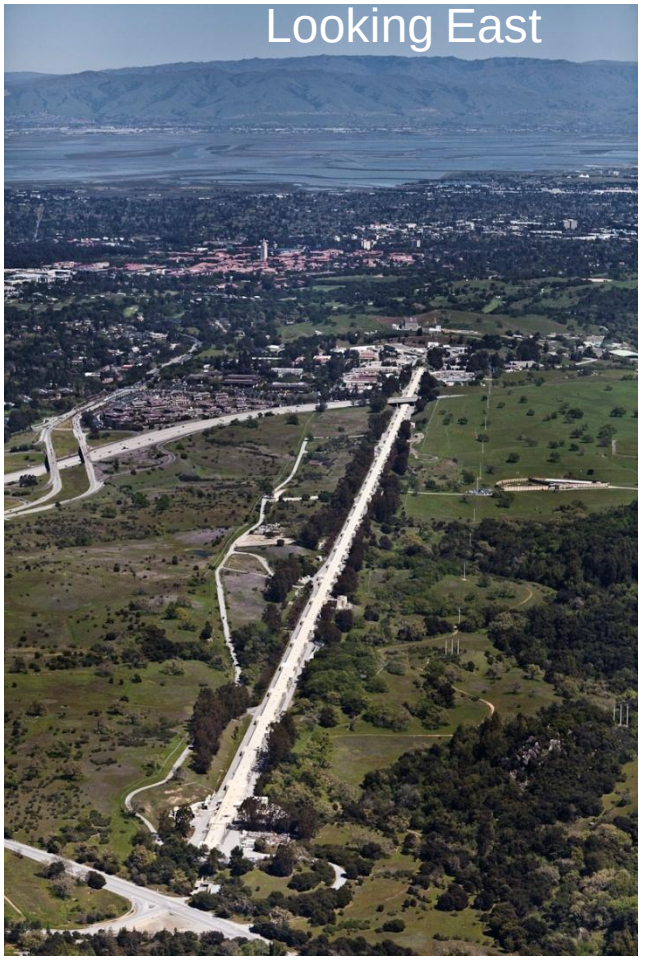
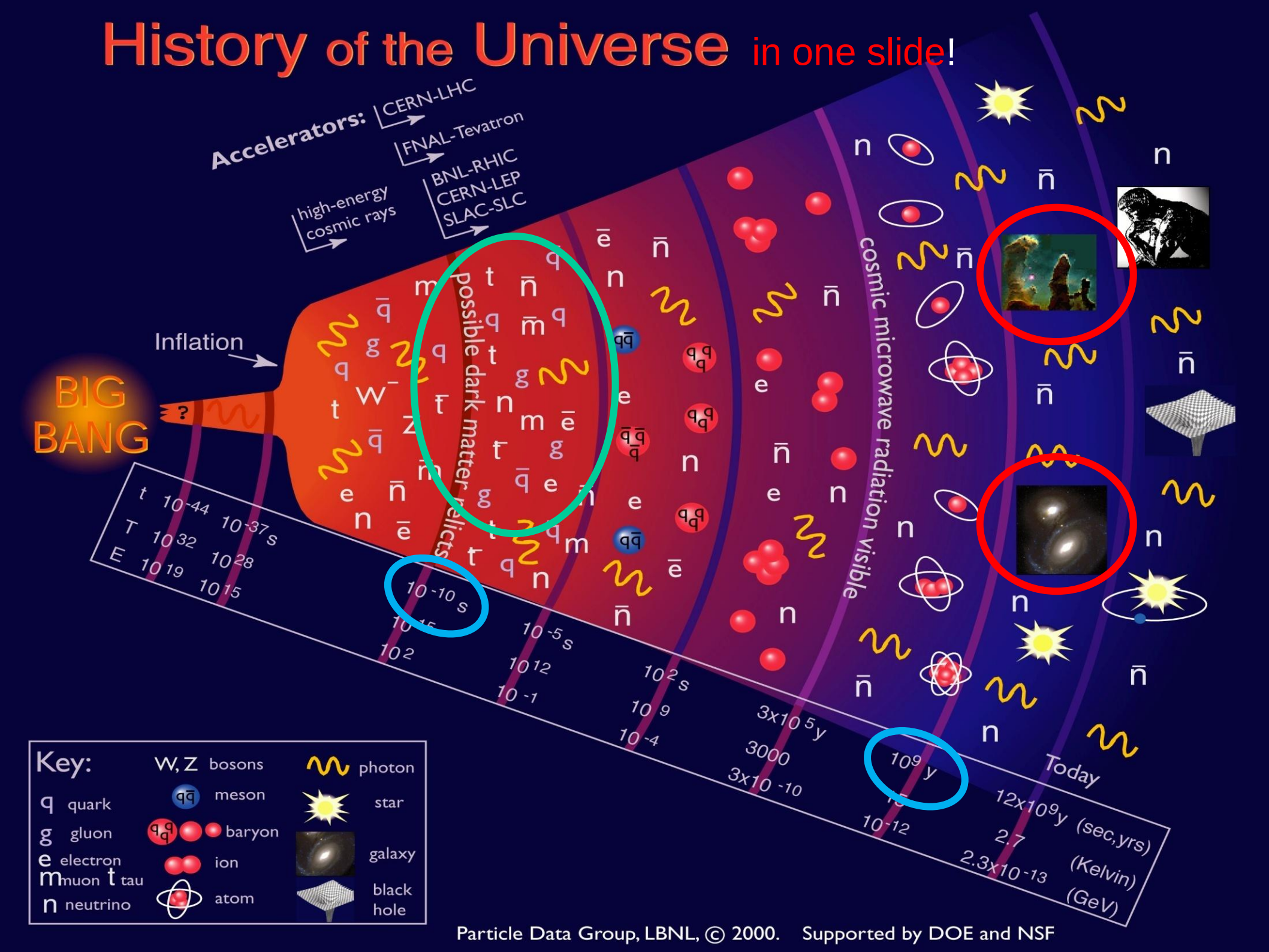


Astrophysics

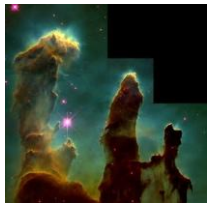
Studying the very large requires scaling up your tools in a very large way.

History of the Universe in one slide!



But – much more than that to our current picture of the Universe, which is actually kind of… ***Cupcake-like***!

Sprinkles = Normal Matter: ~4%


Frosting = Dark matter: ~26%

Main Cupcake: Dark energy: ~70%

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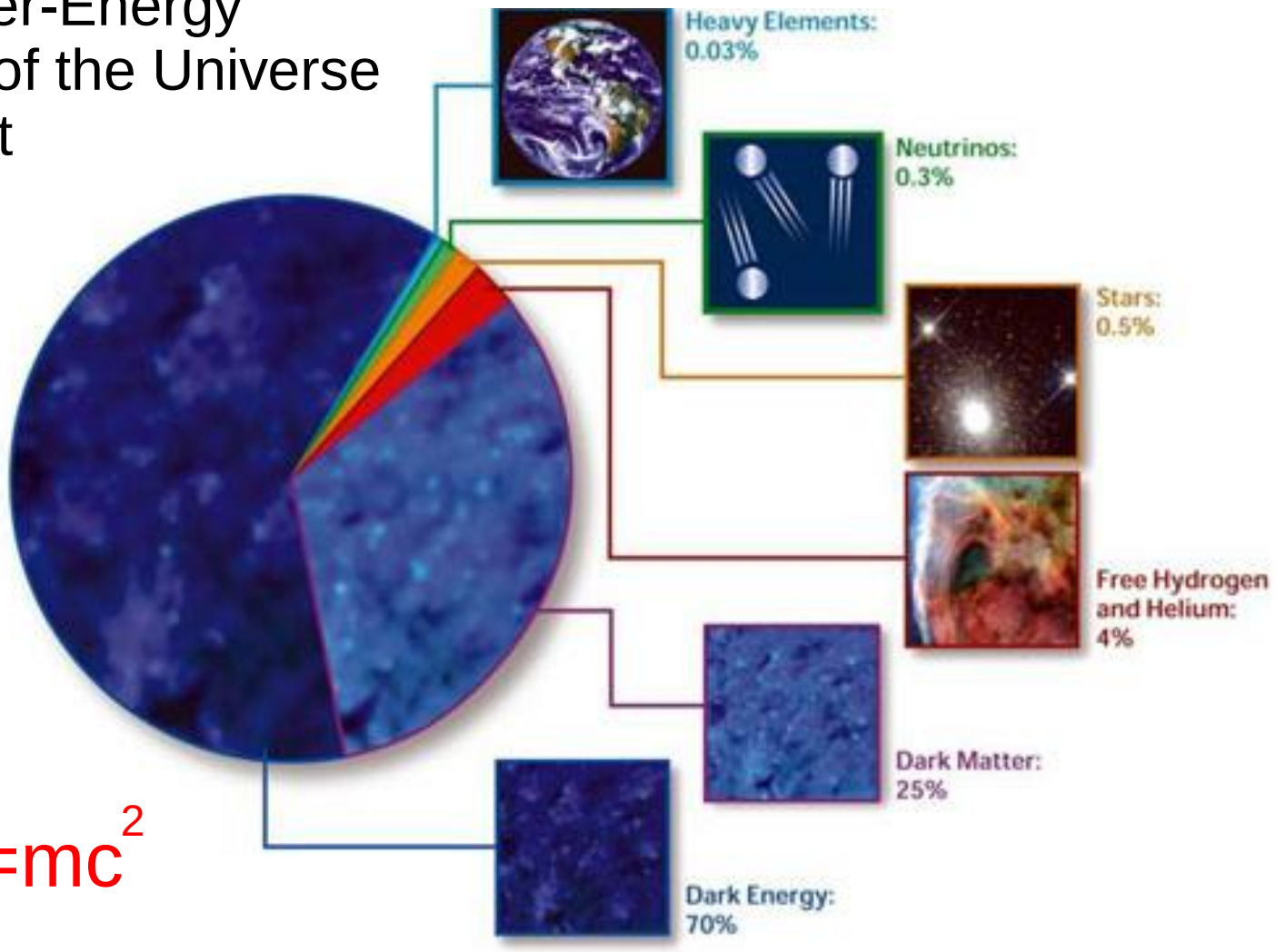
The biggest mystery in all science..??!

Shown: Matter-Energy composition of the Universe as a pie chart



Implicit here: $E=mc^2$

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Why do we believe in DM? Let's start in 1689: Newton explains the motion of the planets

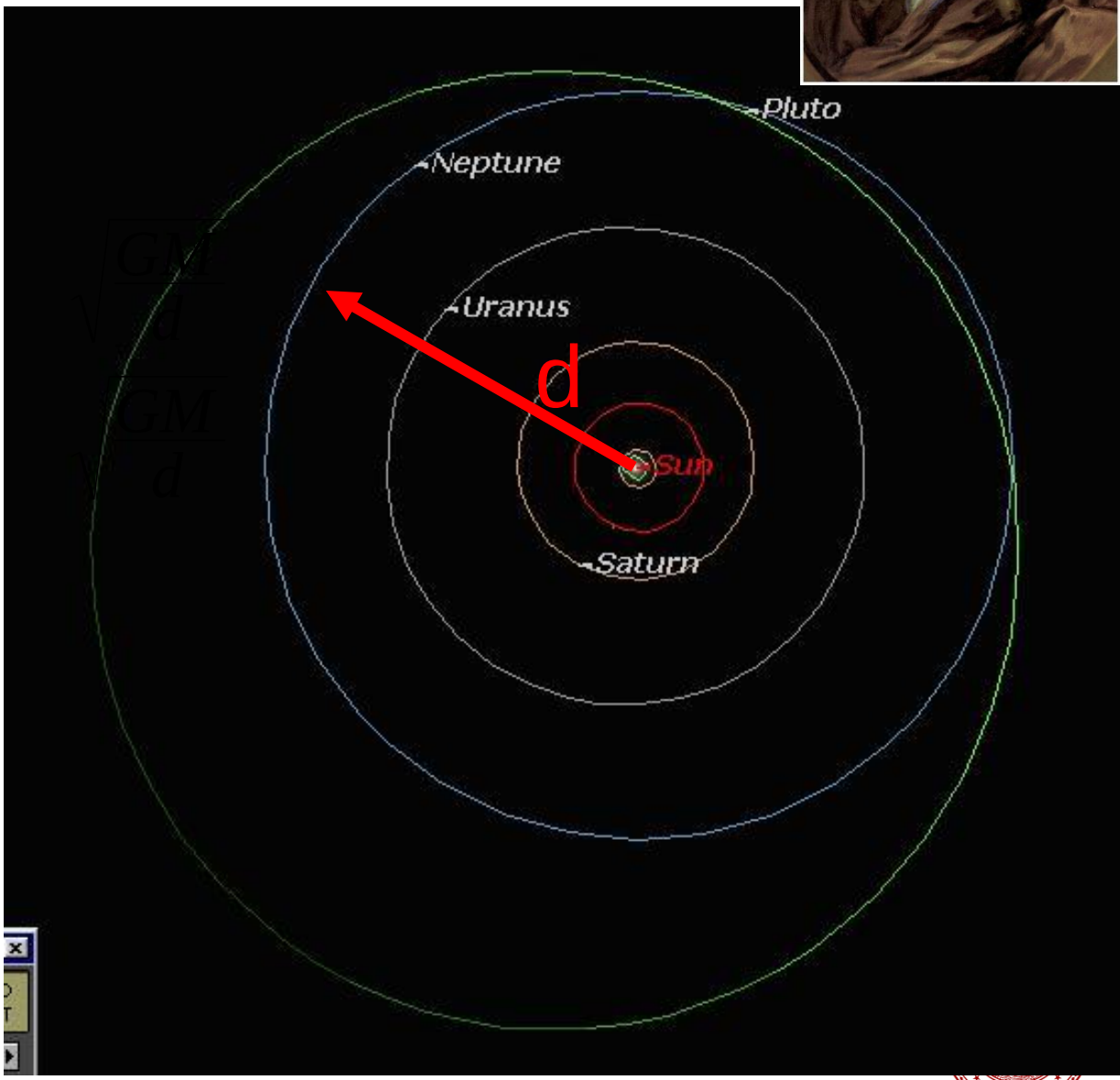
Matter produces force (Universal Gravity)

Force causes acceleration

$$F = \frac{GMm}{d^2}$$

$$a = \frac{F}{m} = \frac{v^2}{d}$$

$$v = \sqrt{\frac{GM}{d}}$$



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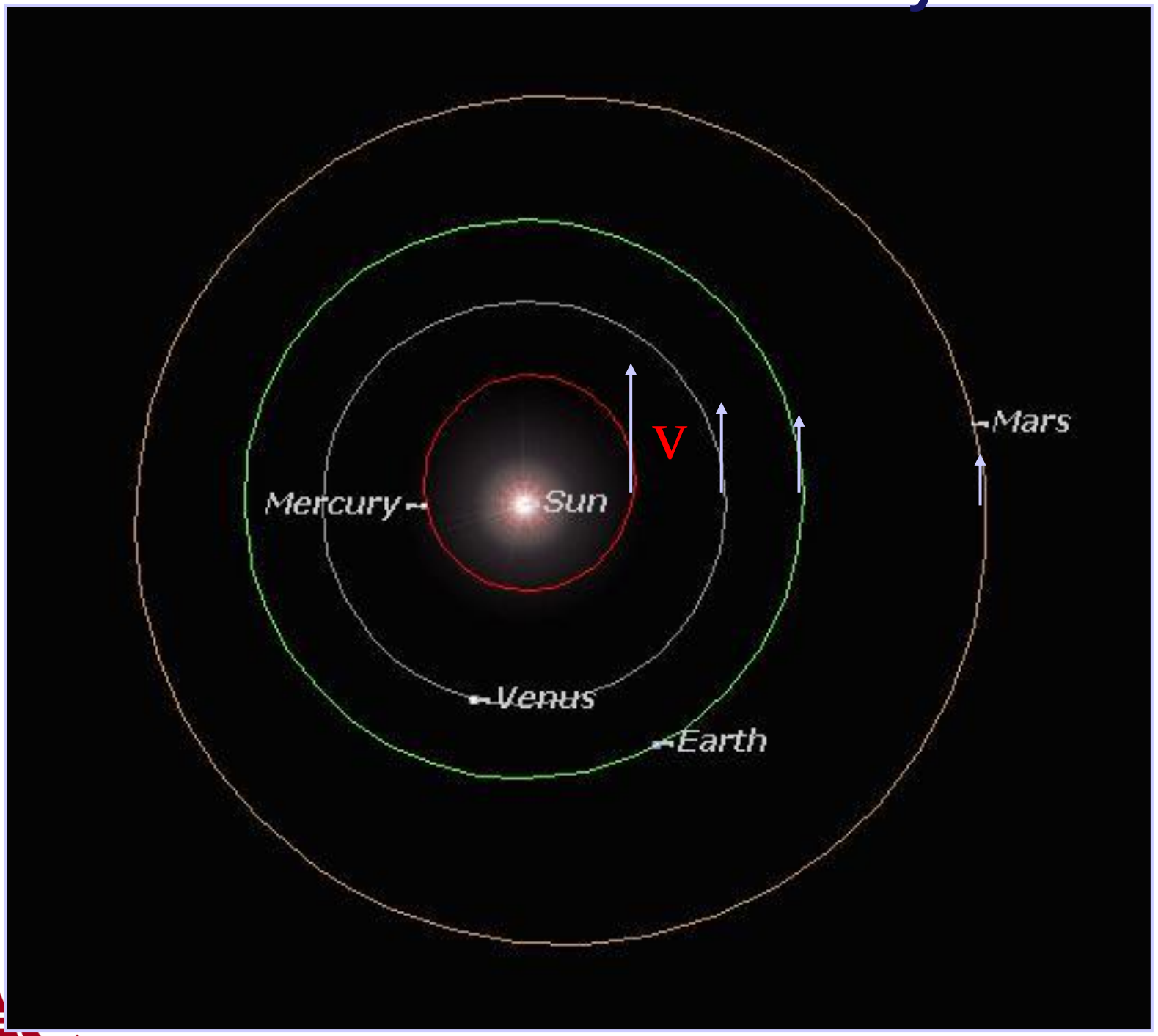
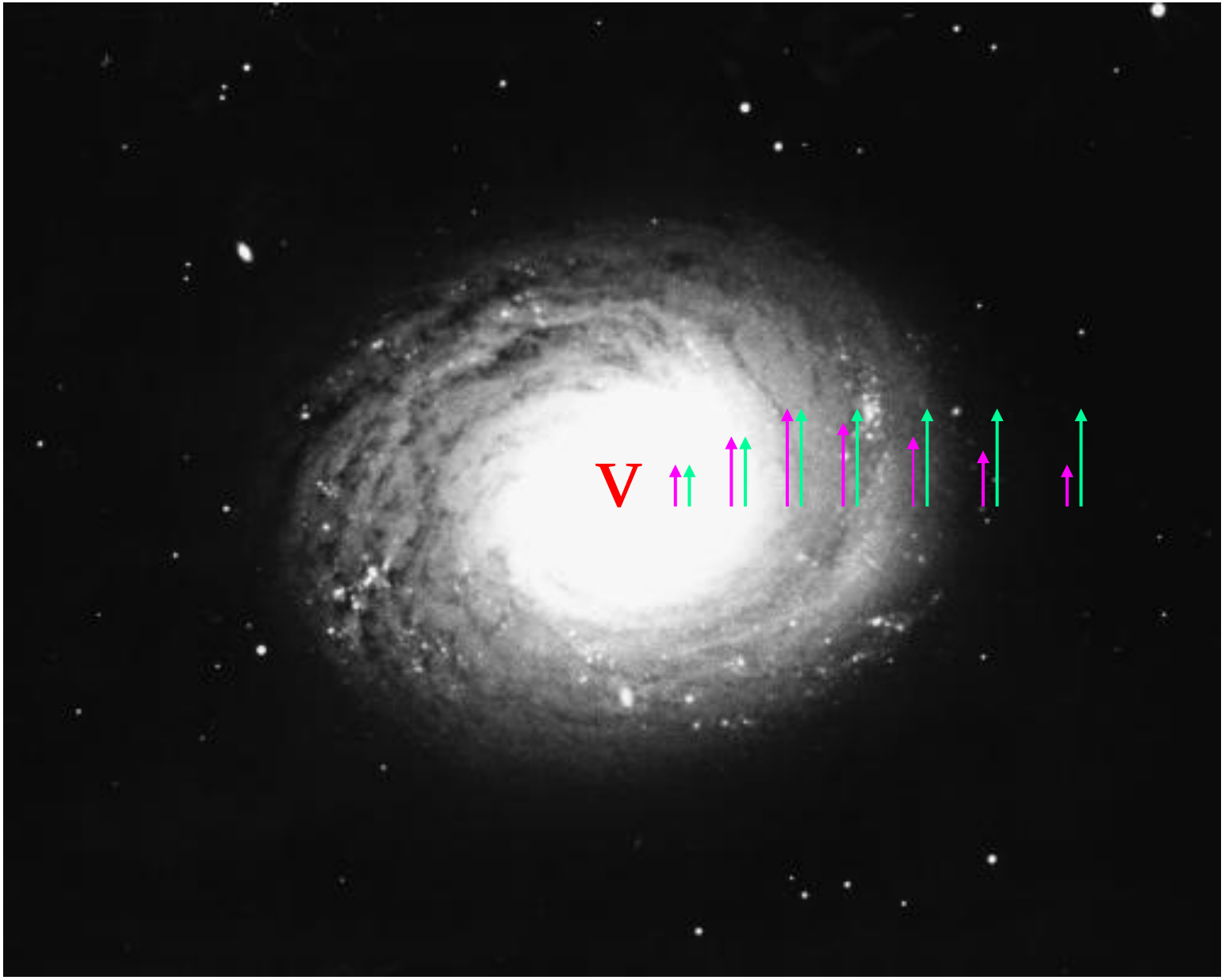
And we see in the Solar System:



In Galaxies we expected:

But we measure (green arrows):



!!!!

DM and Galaxy Stellar Orbital Speeds

- Thus we infer there's some other kind of matter we can't see in visible light *directly*.
- Evidence for it is all from gravity:
  - Velocity (measured by Doppler Shift) of stars and gas clouds imply mass of galaxy continues beyond visible edge.

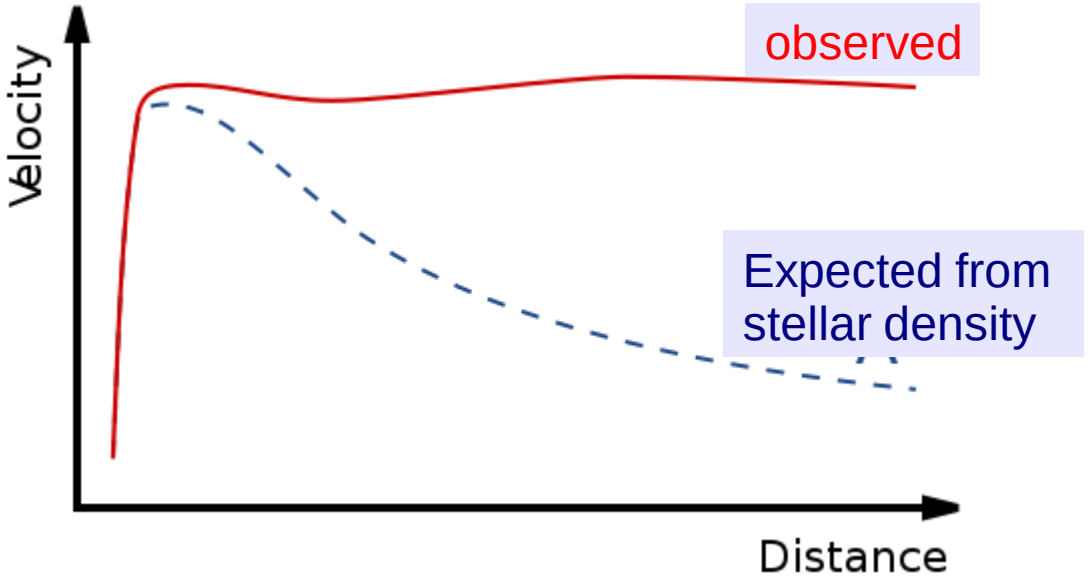
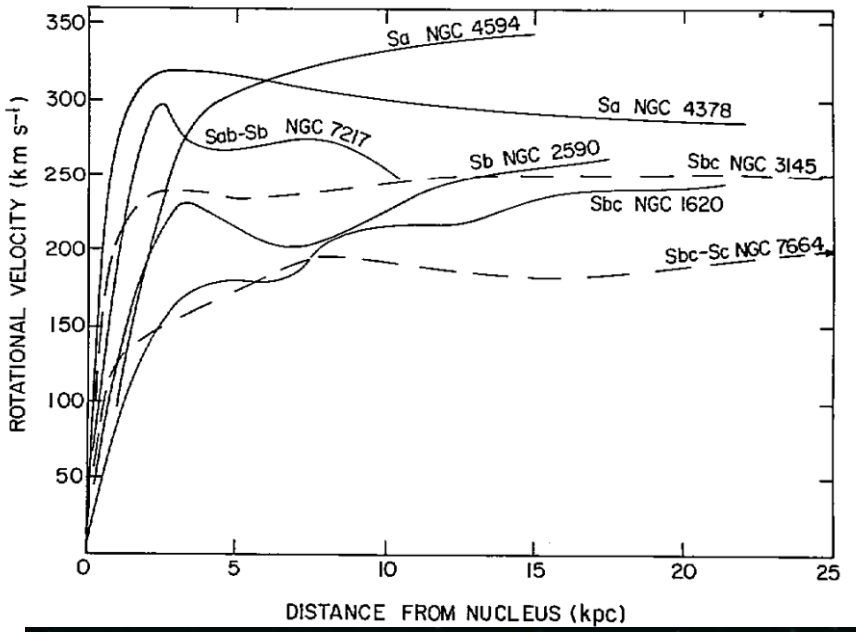
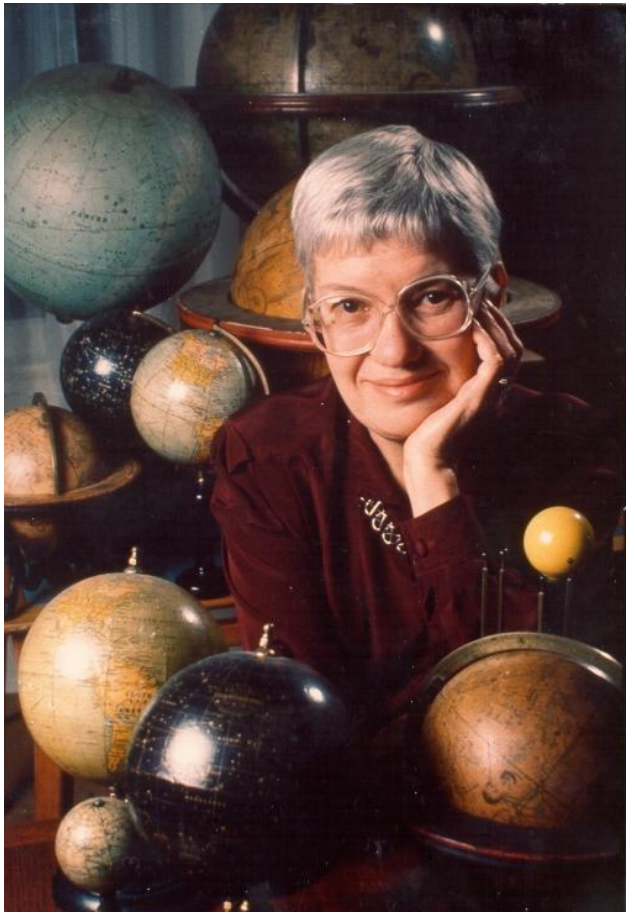


Image credit: wikipedia

Distance from center of galaxy

Mid-1970s -- Rubin, Ford, Roberts, and others saw that: Spiral galaxies have flat rotation curves

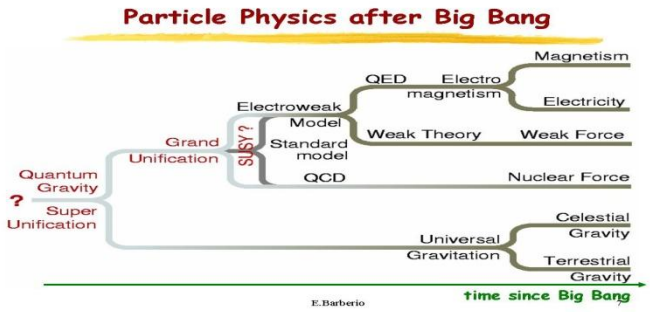




Dark Matter is indirectly "seen" in many arenas

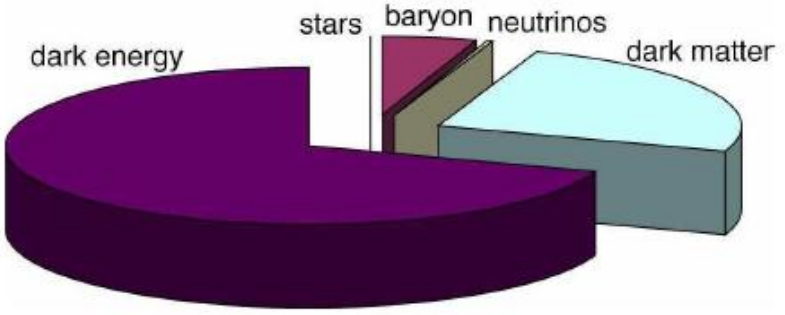
Galaxy Dynamics &:
- Galaxy cluster dynamics
- Gravitational Lensing
- Large Scale Structure
- Baryon Acoustic Oscillations
- Cosmic Microwave Background

Particle Theory



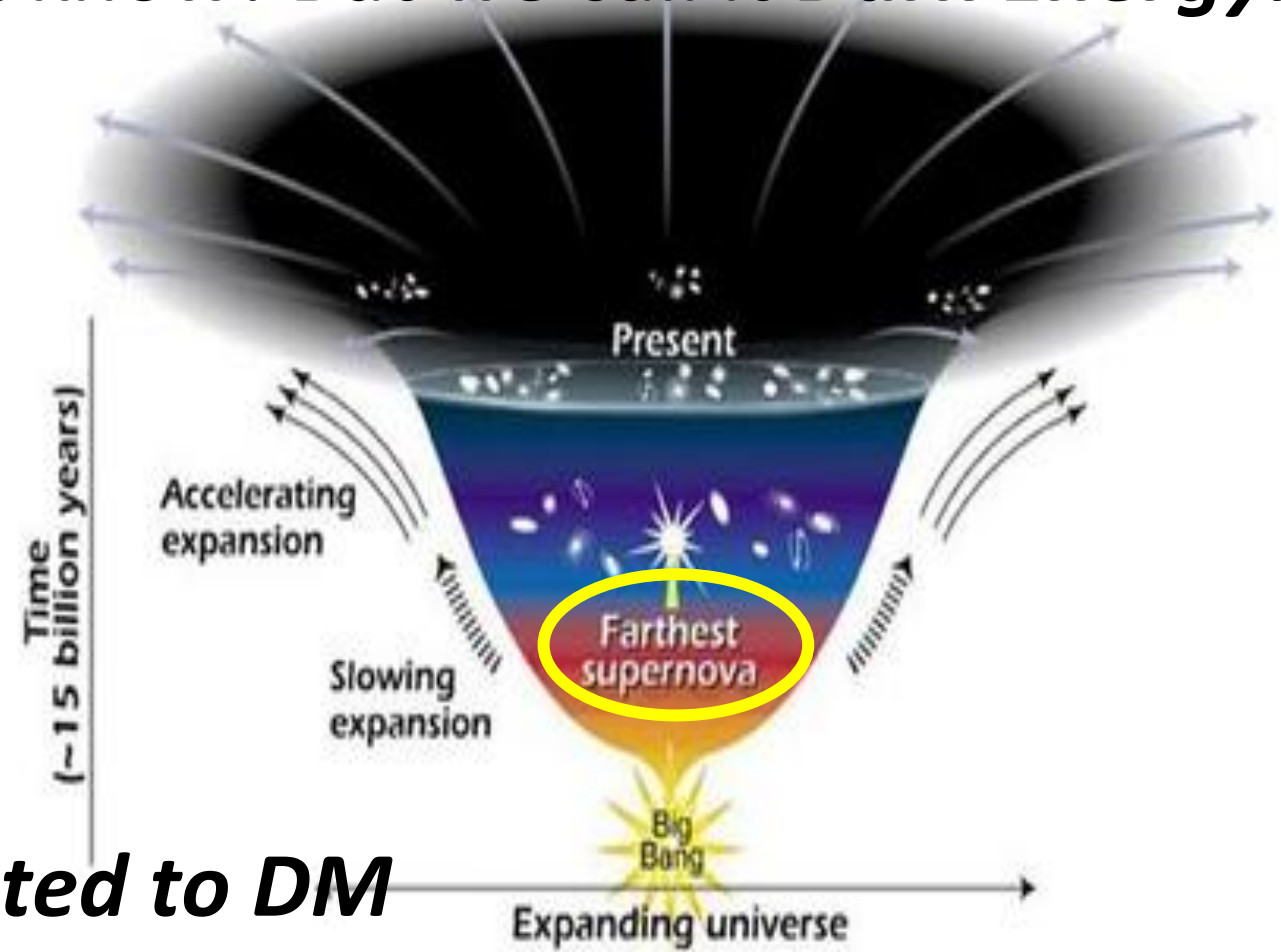
And searched for in others: Colliders + direct DM detection expts

Cosmological Component



Next: What's Dark Energy (DE) ?

- 1998: Discovery that expansion of the universe is accelerating... what's driving this? (c.f. 2012 Nobel Prize in Physics)
- We don't know! But we call it ***Dark Energy.***

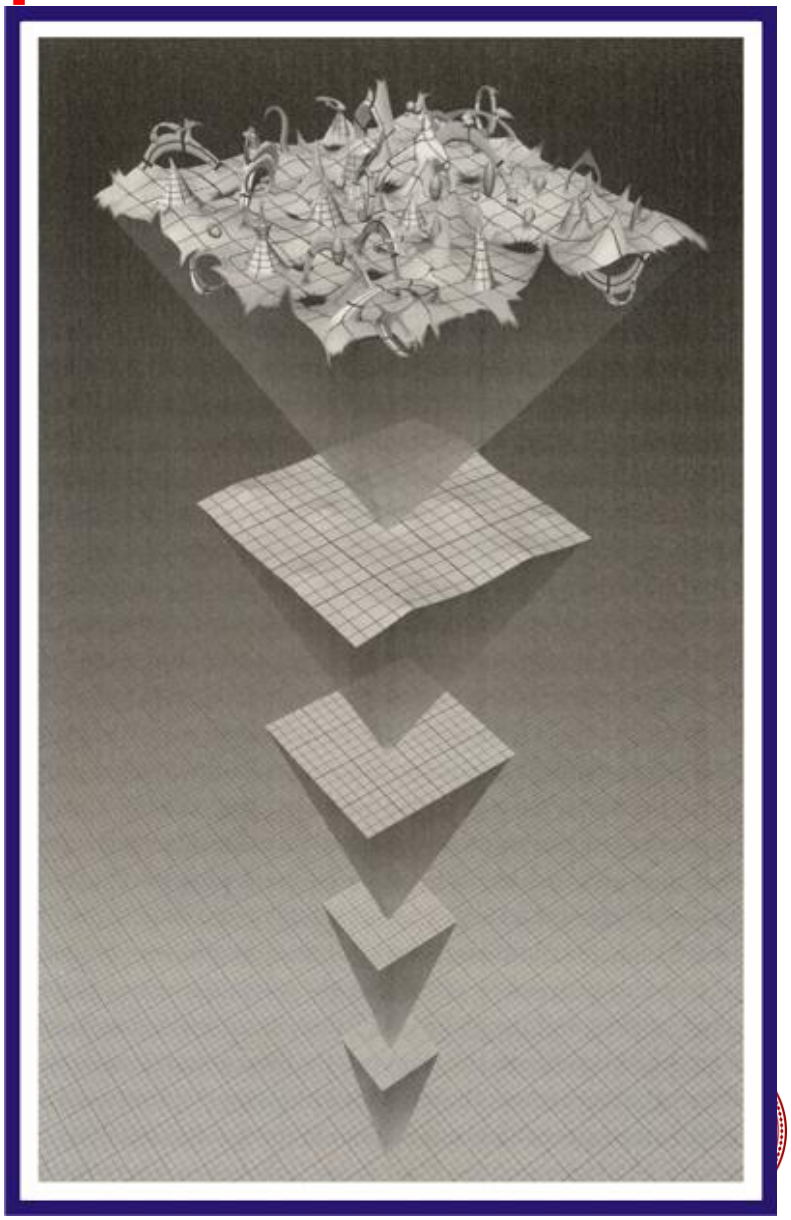


- ***NOT related to DM***

At smallest scales, vacuum is a writhing mass of particles

We already see this at some level (cf. *Casimir Effect*) for charged particles.

But if spacetime becomes "foamy" at the Planck Length, then we expect the vacuum to have 10^{128} (!!!) times as much energy as is seen.



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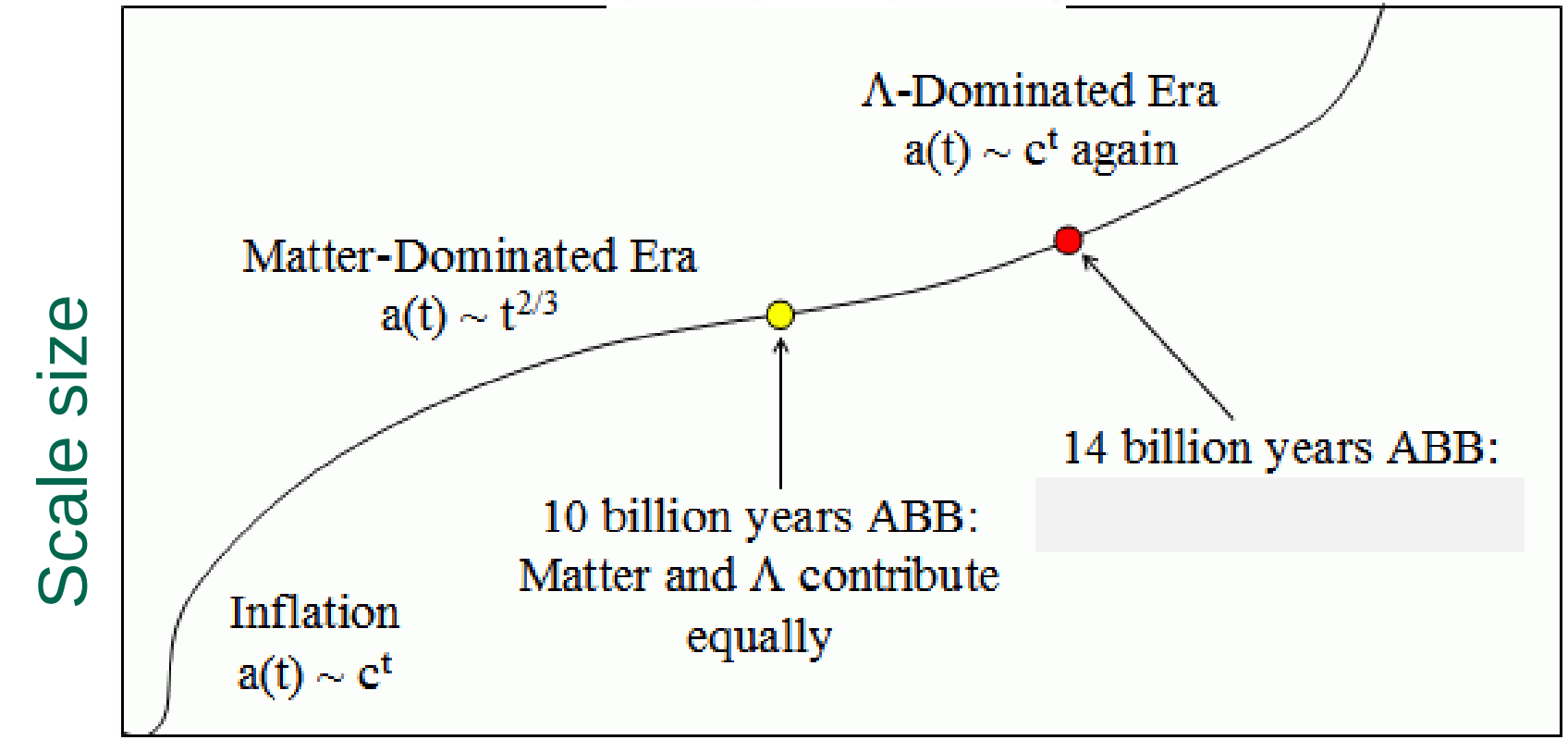
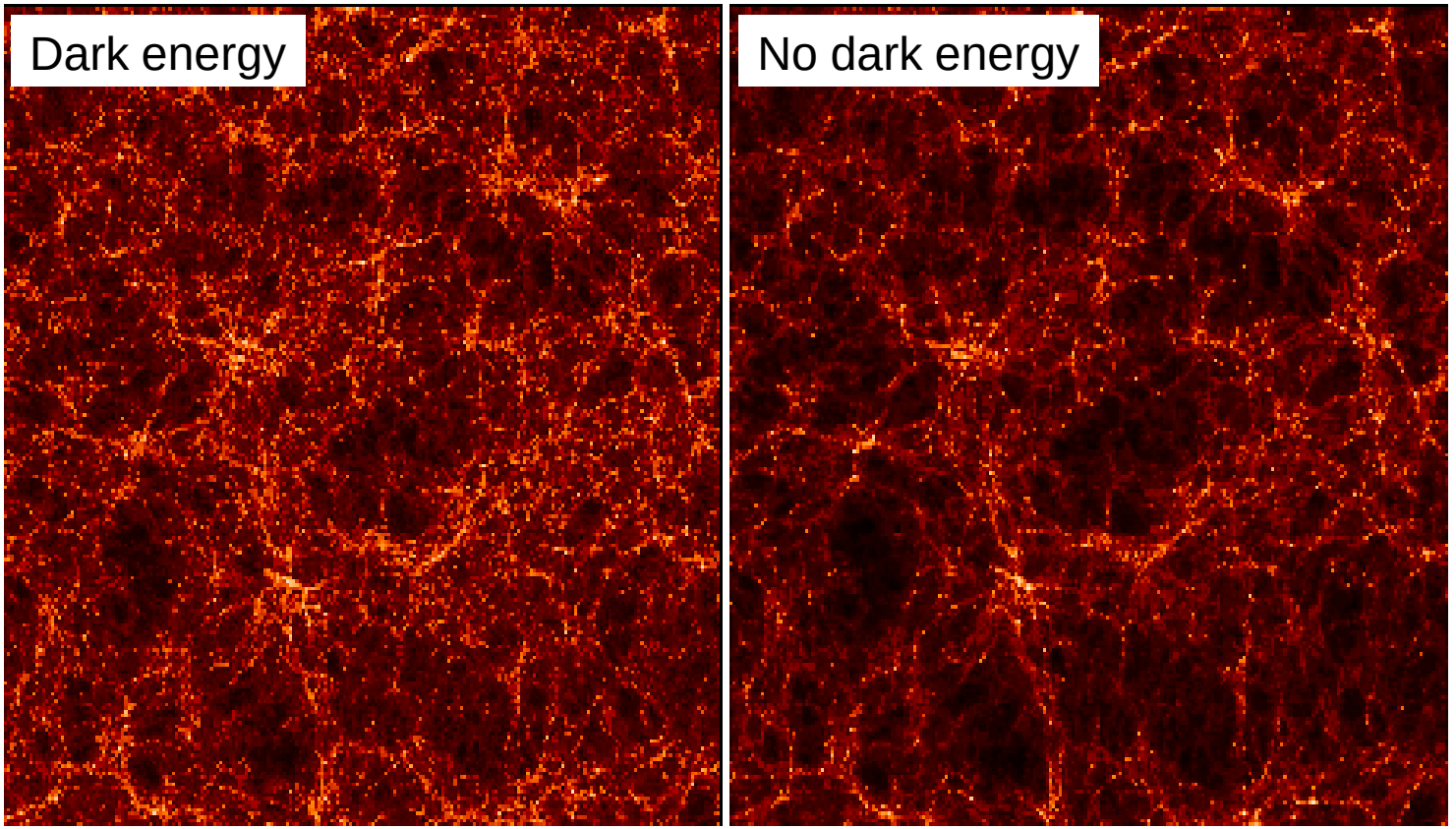

Λ-Dominated Era
a(t) ~ c^t again
Matter-Dominated Era
a(t) ~ t^2/3
14 billion years ABB:
10 billion years ABB:
Matter and Λ contribute
equally
Inflation
a(t) ~ c^t
Scale size
Time

Another place we see DE: Simulations of Large Scale Structure of matter in the universe

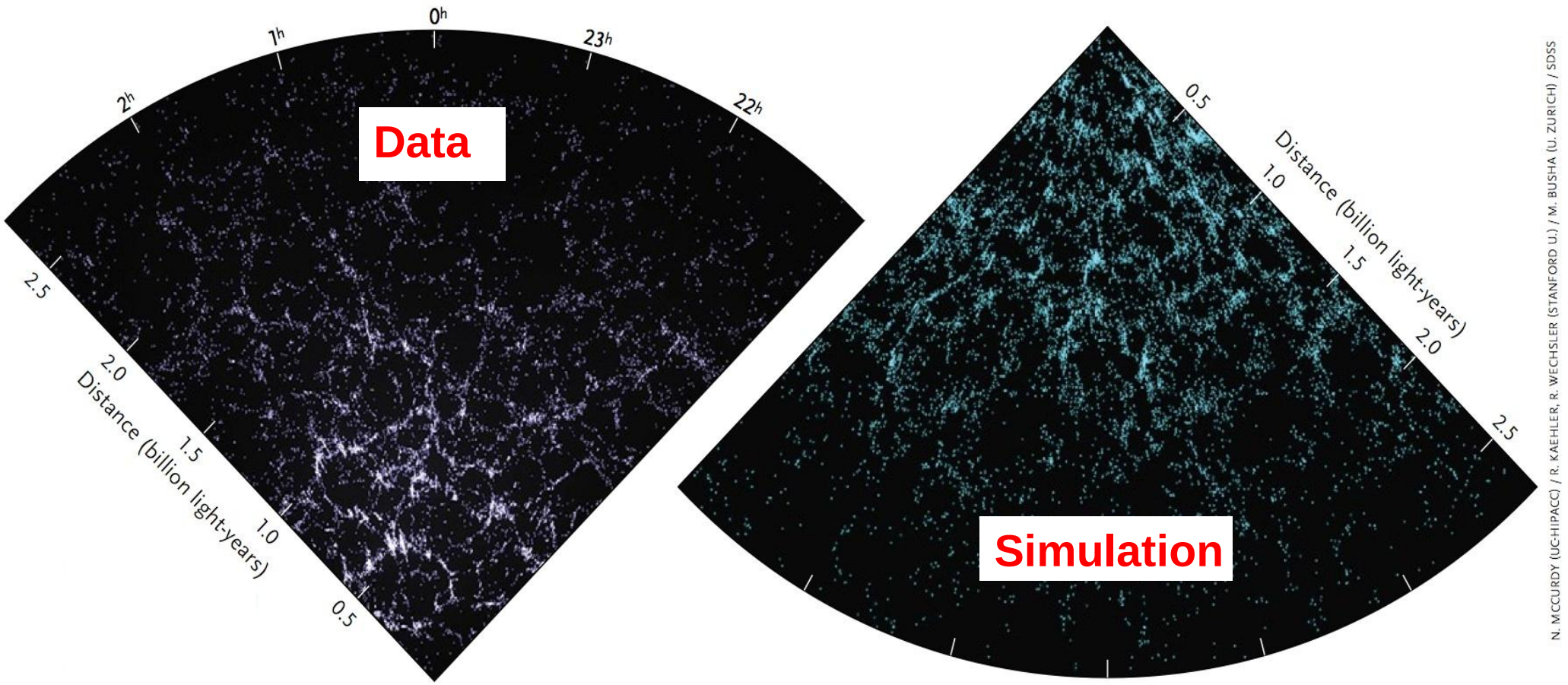
12 billion years ago



The VIRGO Collaboration 1996

[Show simln]

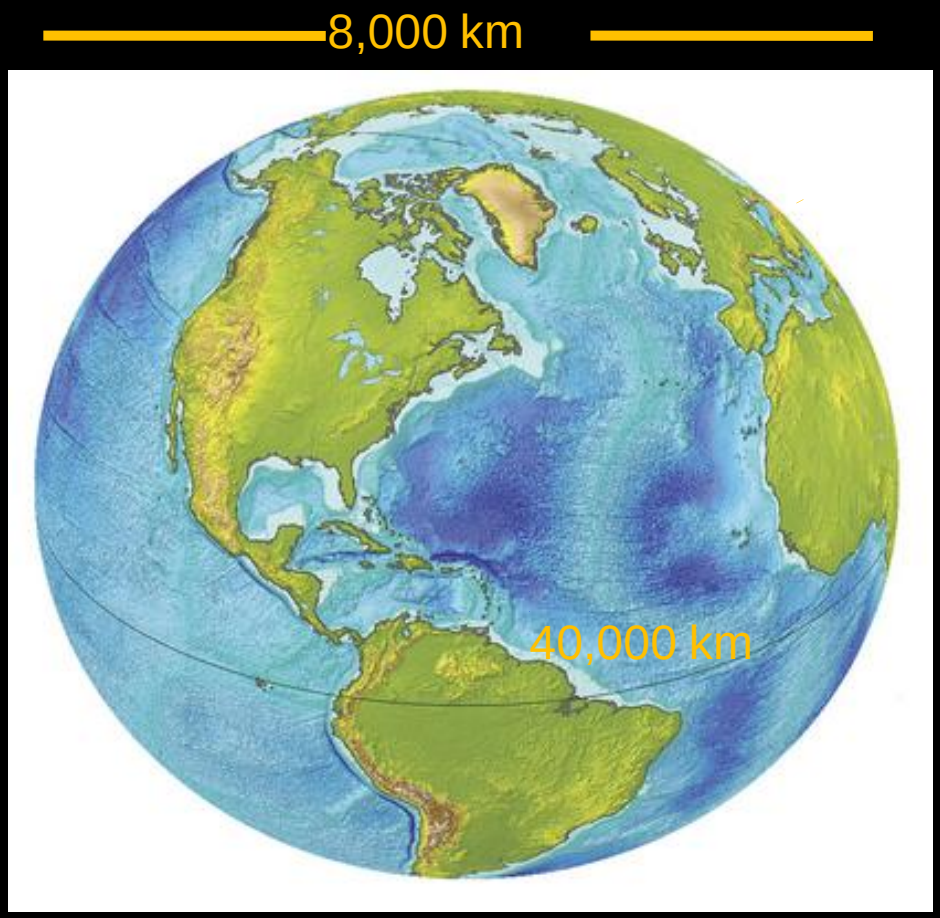
Now compare Data vs. Simulation – very similar

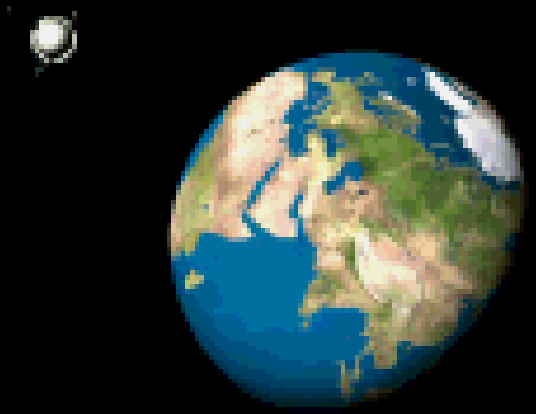


Simulation of a universe with 23% dark matter and 72% dark energy

How are we ever going to figure this out..?

First let's step back to what we know. For a sense of scale: begin close to home with travels around the Earth's circumference





Fastest Low Earth Orbit Satellites: ~30,000 kph

Elapsed Time for Orbit: ~90 min

How about for Light?

1/8 of a second!

From 'Near' to Far:

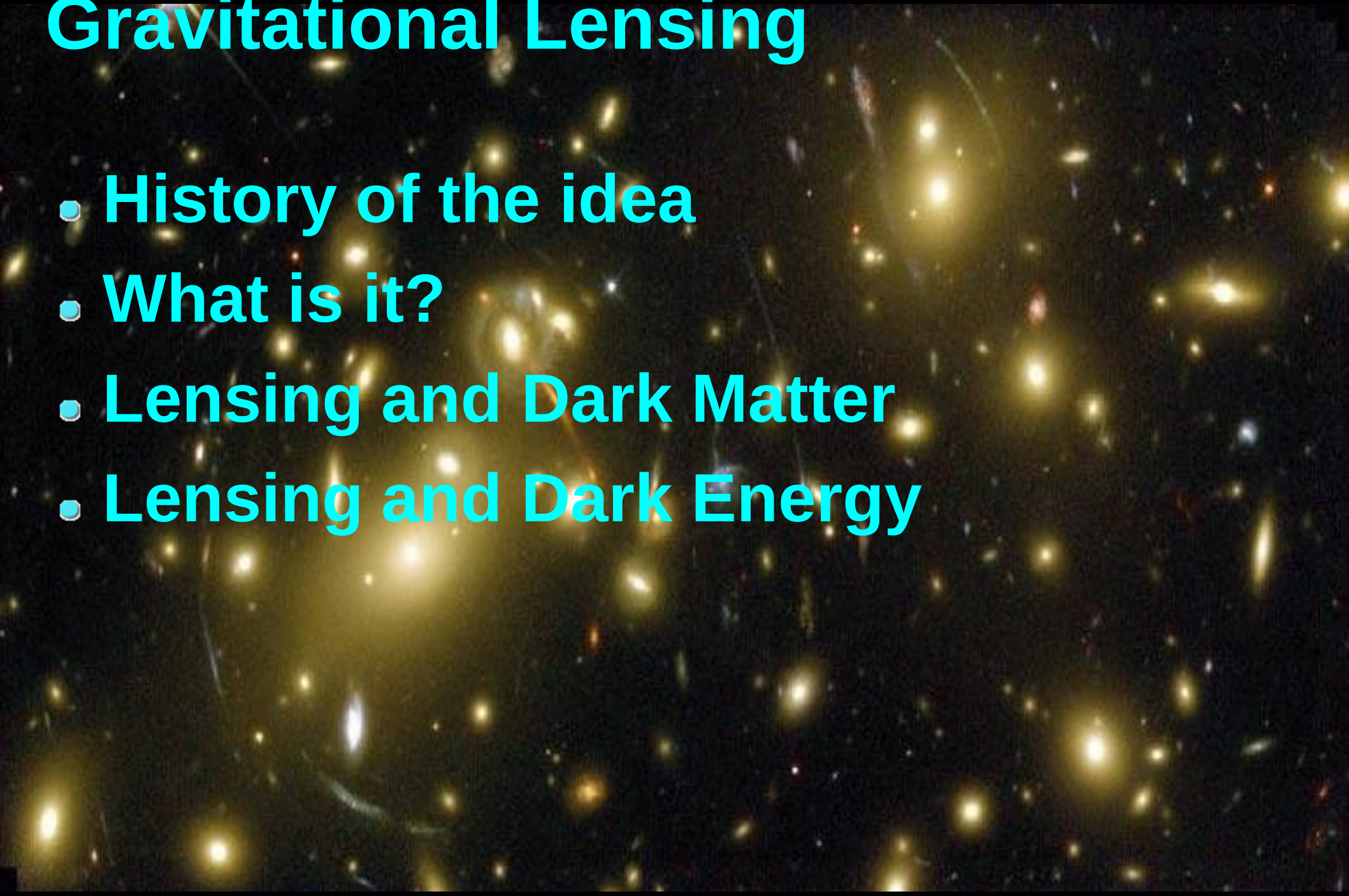
Step out in distances:

Earth's circ. – 0.13 light sec
the Moon -- 1.3 light sec
Sun -- 8.3 light min
Mars -- 14 light min
Neptune -- 5 light hrs
Pluto -- 6 light hrs
Voyager 1 -- 17 light hrs
Oort Cloud - ~5 light months
Alpha Centauri System - ~4 lyr
Solar Nbhd - ~20 lyr
Big Dipper Stars - ~70-120 lyr
Betelgeuse and Rigel - ~650, 860 lyr
MWG center - ~30 klyr
Andromeda - ~2.6 Mlyr
Nearby galaxies - ~10-100 Mlyr
Farthest visible objects - ~13 Glyr

→ Limit of Observable Universe:

CMB (Cosmic Microwave Background) - 13.8 Glyr

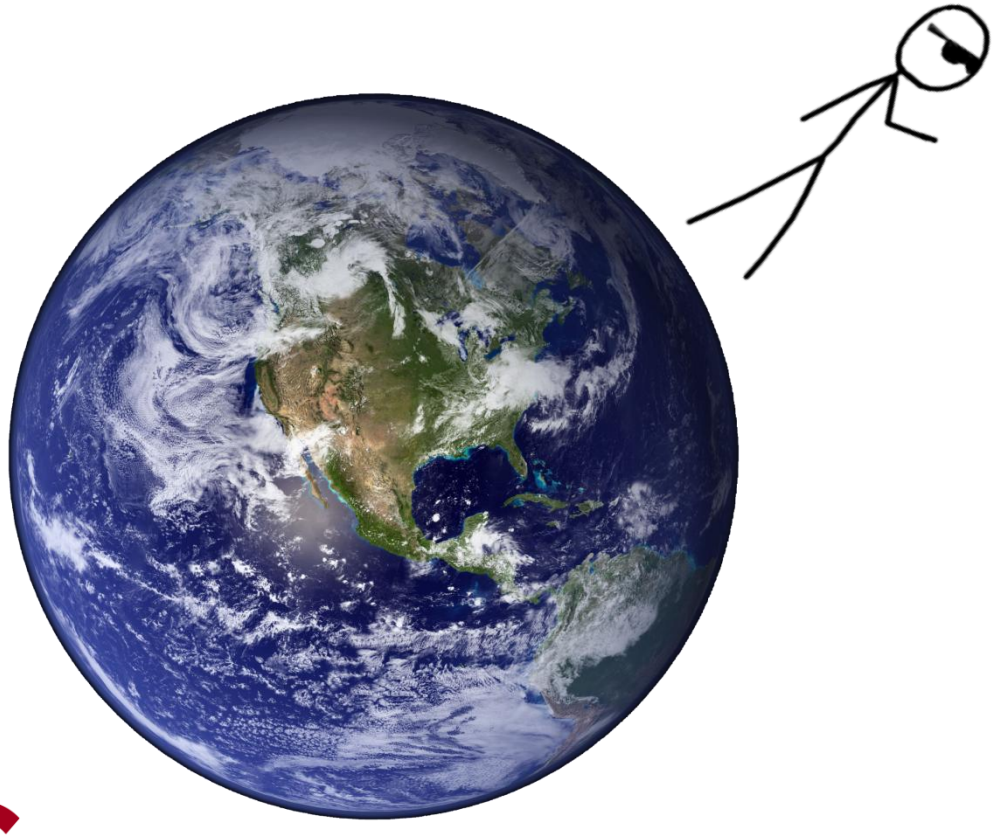
Gravitational Lensing



- History of the idea
- What is it?
- Lensing and Dark Matter
- Lensing and Dark Energy

What does gravity do?

- Holds us on to the Earth...



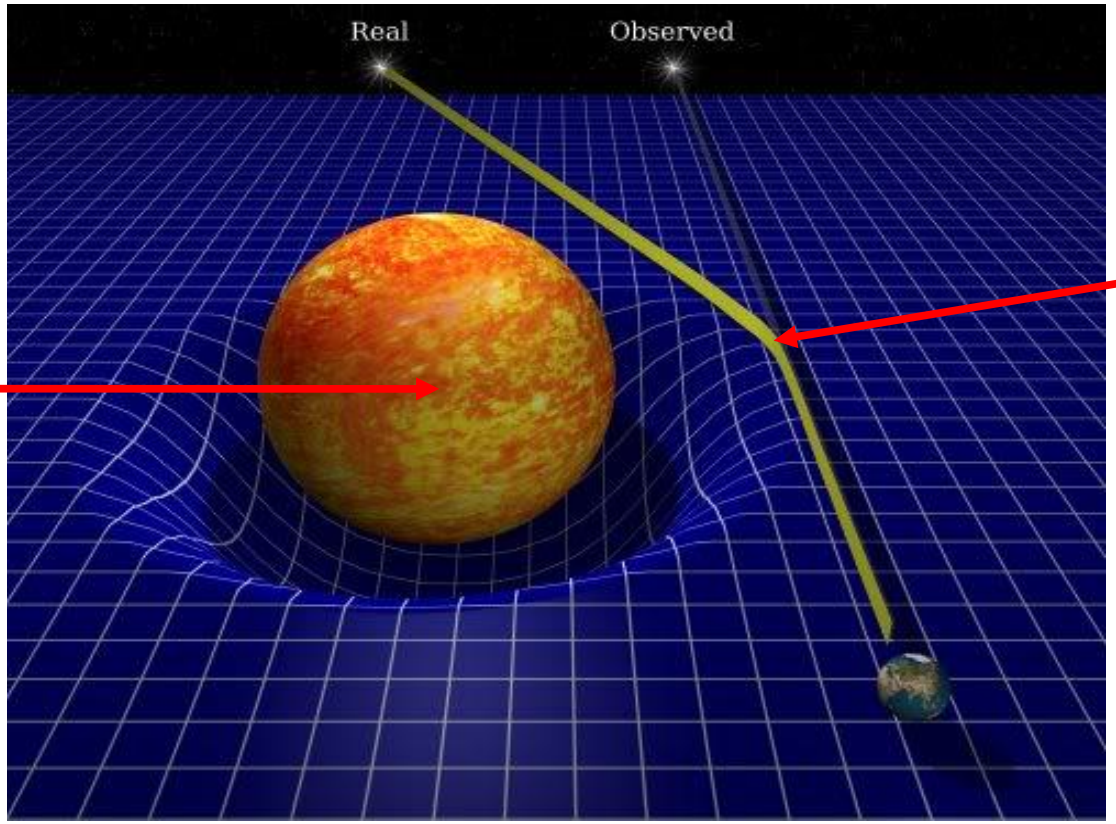
What does gravity do?

- Holds us on to the Earth...
- Holds the Earth in orbit around the Sun...

What does gravity do?

- Holds us on to the Earth...
- Holds the Earth in orbit around the Sun...
- And *bends light!*

Massive object → large gravitational field



Light ray is deflected by gravitational field

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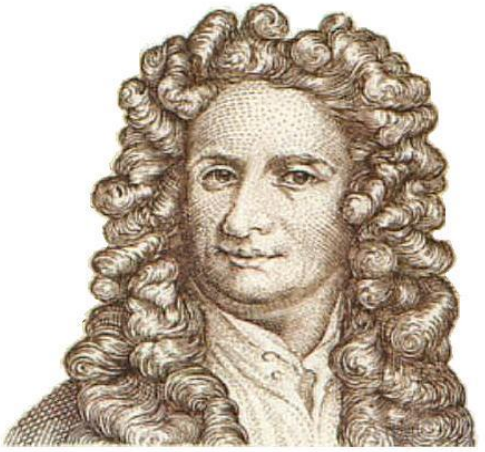
The History of an Idea

- 1687: Newton's Law of Gravity



- 1804: if something is heavy enough, can it deflect light itself? (J. von Soldner)

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The History of an Idea

- 1911: Einstein calculated effect of gravity on light rays

(Factor of 2 relative to Newton)

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The History of an Idea

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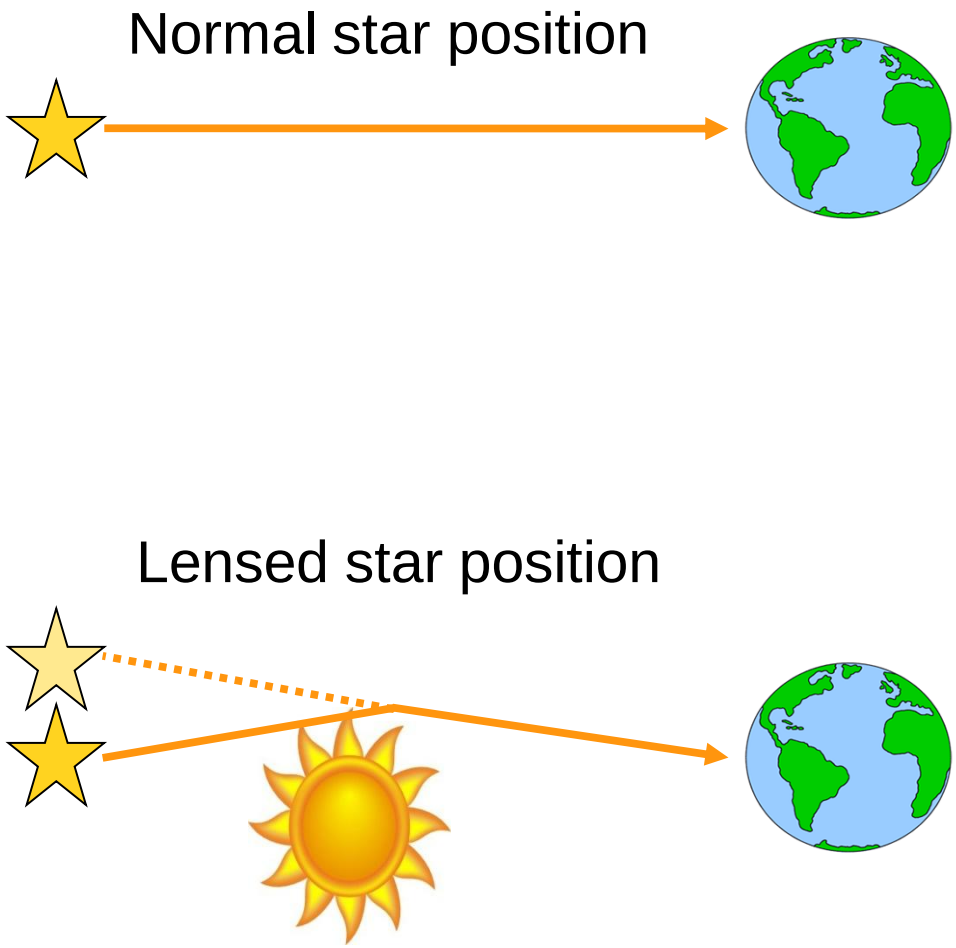
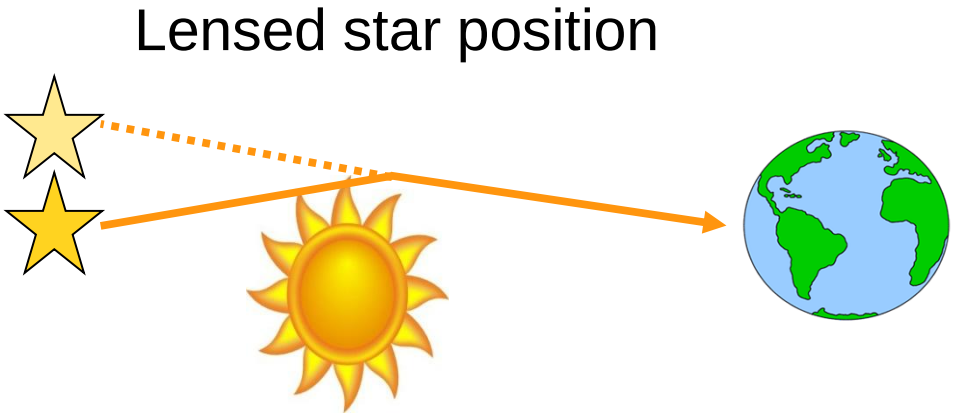


The History of an Idea

1911: Einstein calculated effect of gravity on light rays

- 1919: light observed from star deflected by the Sun during eclipse



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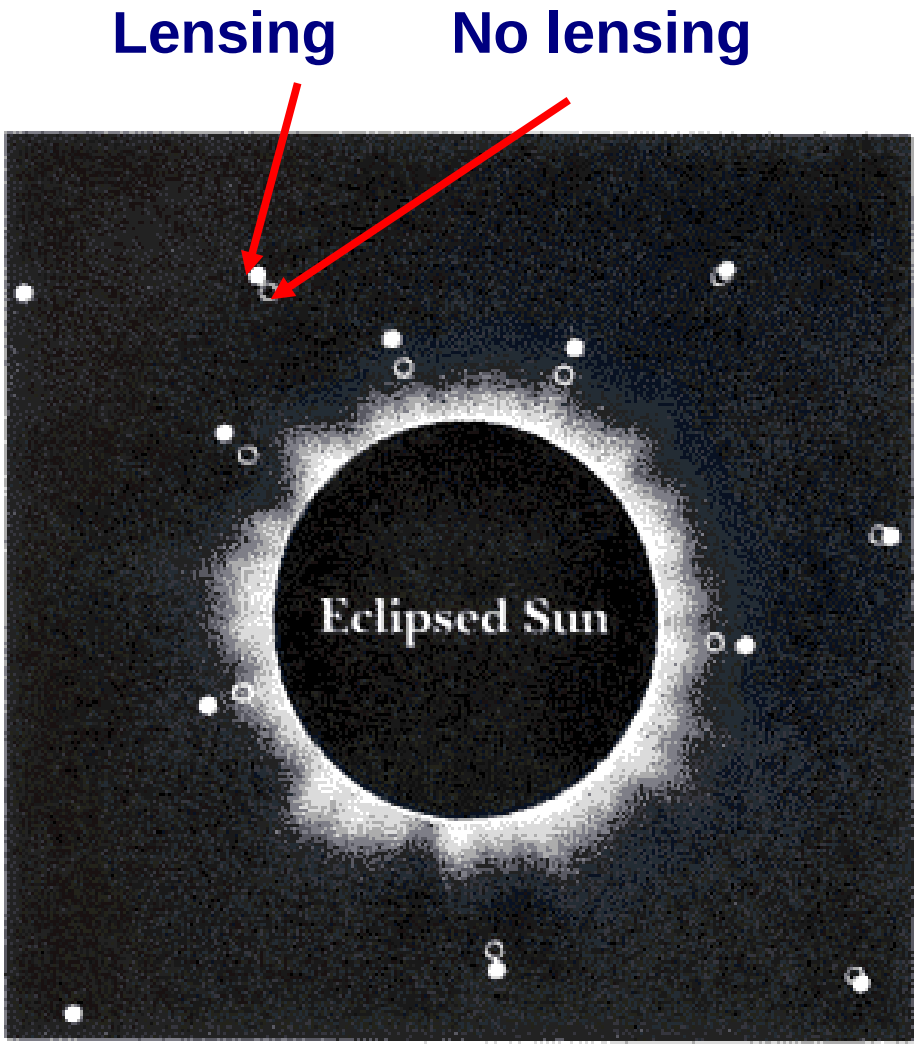

The History of an Idea

- Development of idea that gravity can act as a 'lens'
- In 1936 Einstein described the more dramatic lensing effects (multiple images/ring) and concluded...

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DISCUSSION

LENS-LIKE ACTION OF A STAR BY THE DEVIATION OF LIGHT IN THE GRAVITATIONAL FIELD

Some time ago, R. W. Mandl paid me a visit and
sked me to publish the results of a little calculation
which I had made at his request. This note complies

not decrease like $1/D$, but like $1/\sqrt{D}$, as the distance D increases.

Of course, there is no hope of observing this phenomenon directly. First, we shall scarcely ever approach closely enough to such a central line. Second, the angle β will defy the resolving power of our

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Gravity *lenses* light with several effects

- Image of distant objects is ***distorted*** and ***magnified*** by any gravitational field it passes through.

- What does this actually look like?

- You can play with this-- with a publically available app! (for iPhone, made by KIPACker, Eli R.)

- Check out gravlens3 on iTunes.

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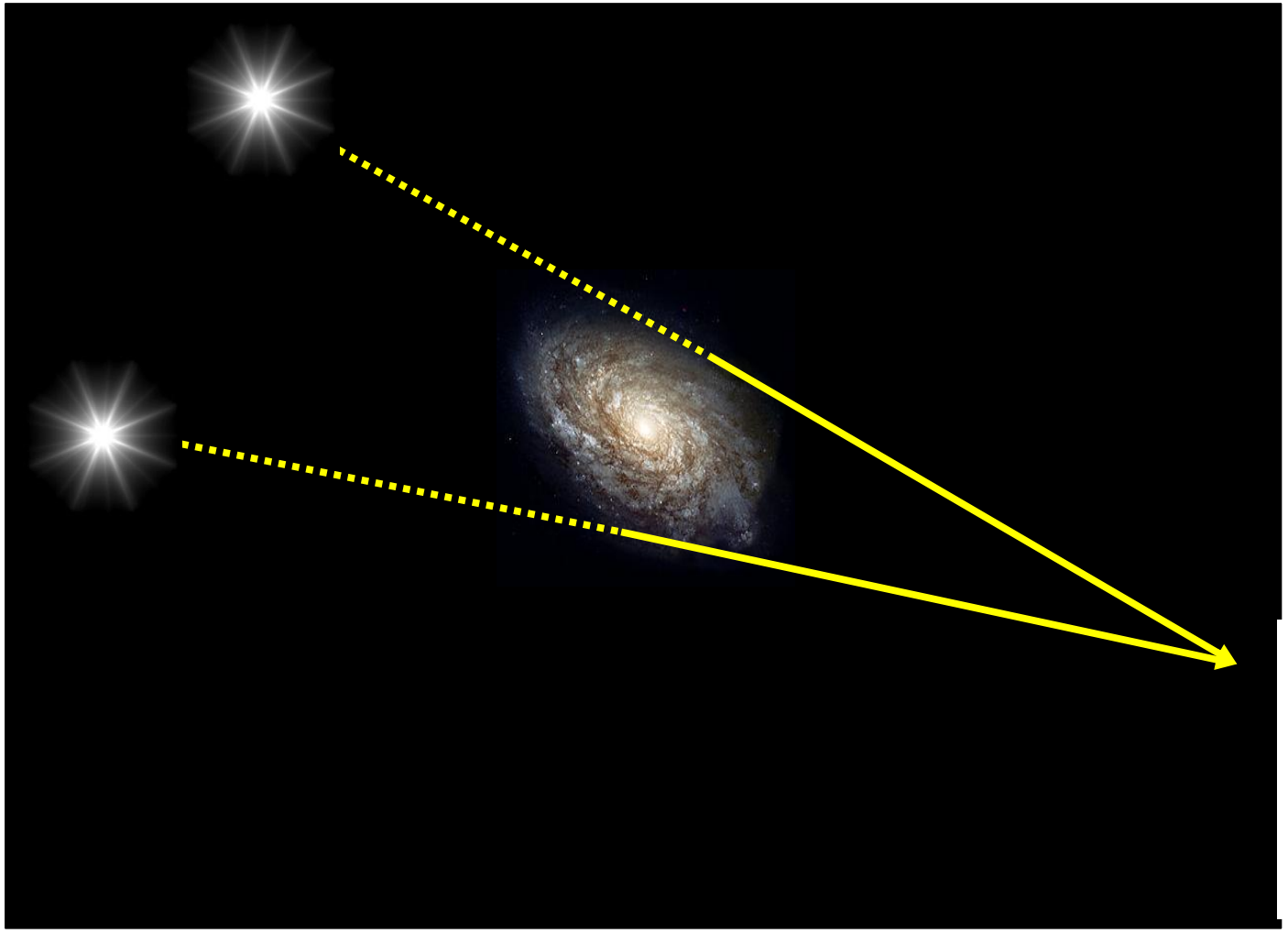
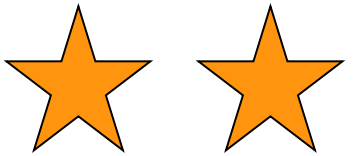
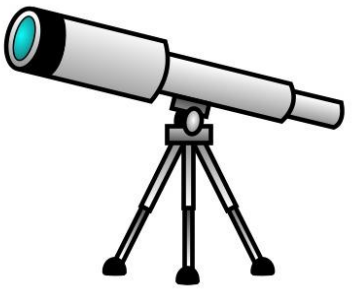
Gravitational lensing: multiple images







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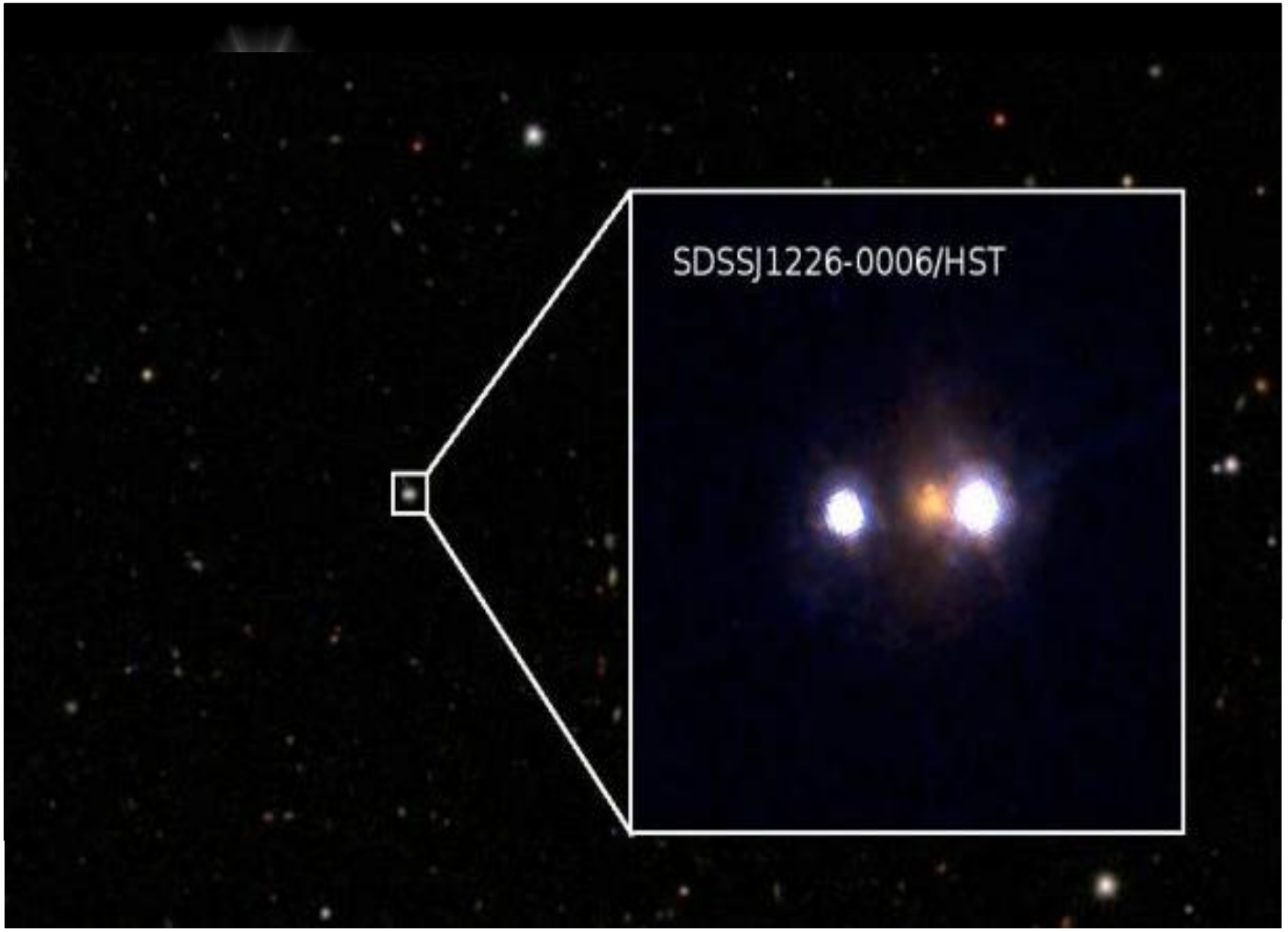
Gravitational lensing: multiple images



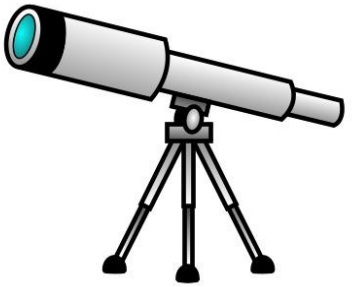


Image Credit: Masamune Oguri, Naohisa Inada et al.

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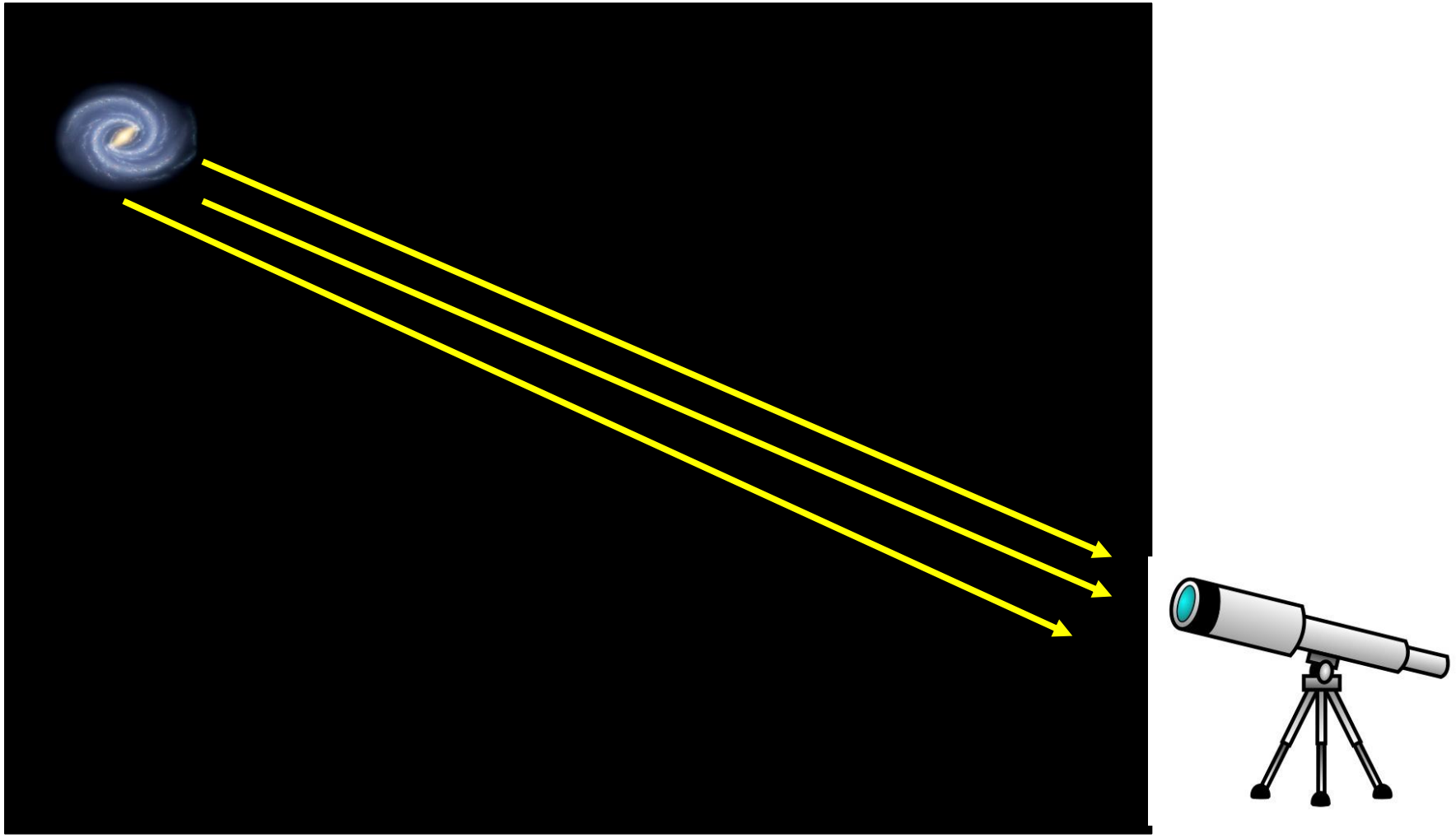
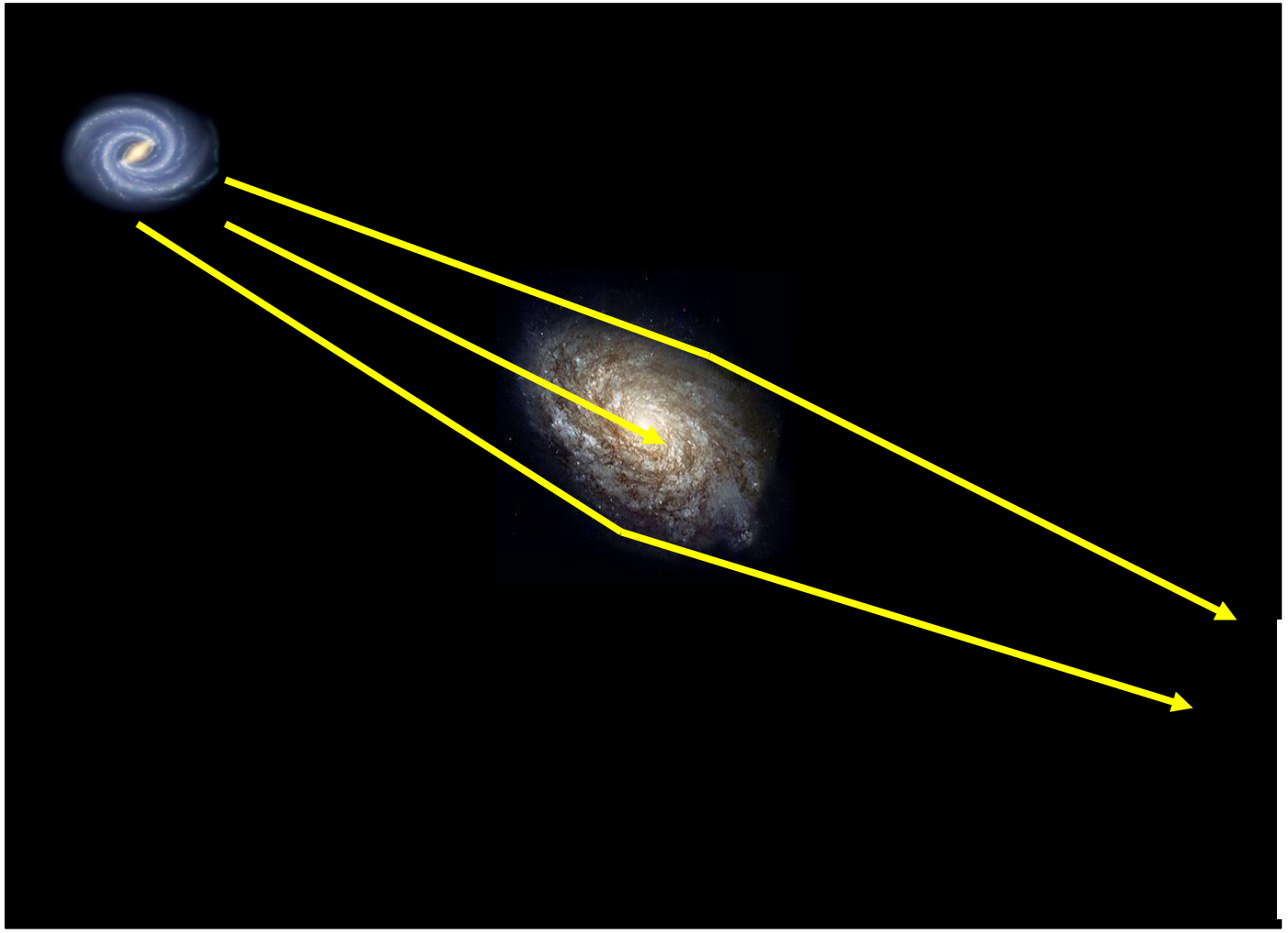
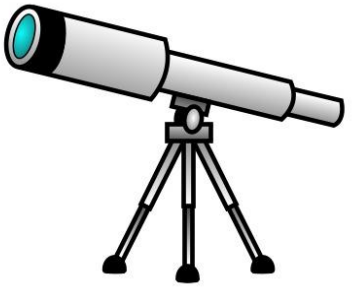
What if you're looking at a galaxy?



And if there's another galaxy in the way?





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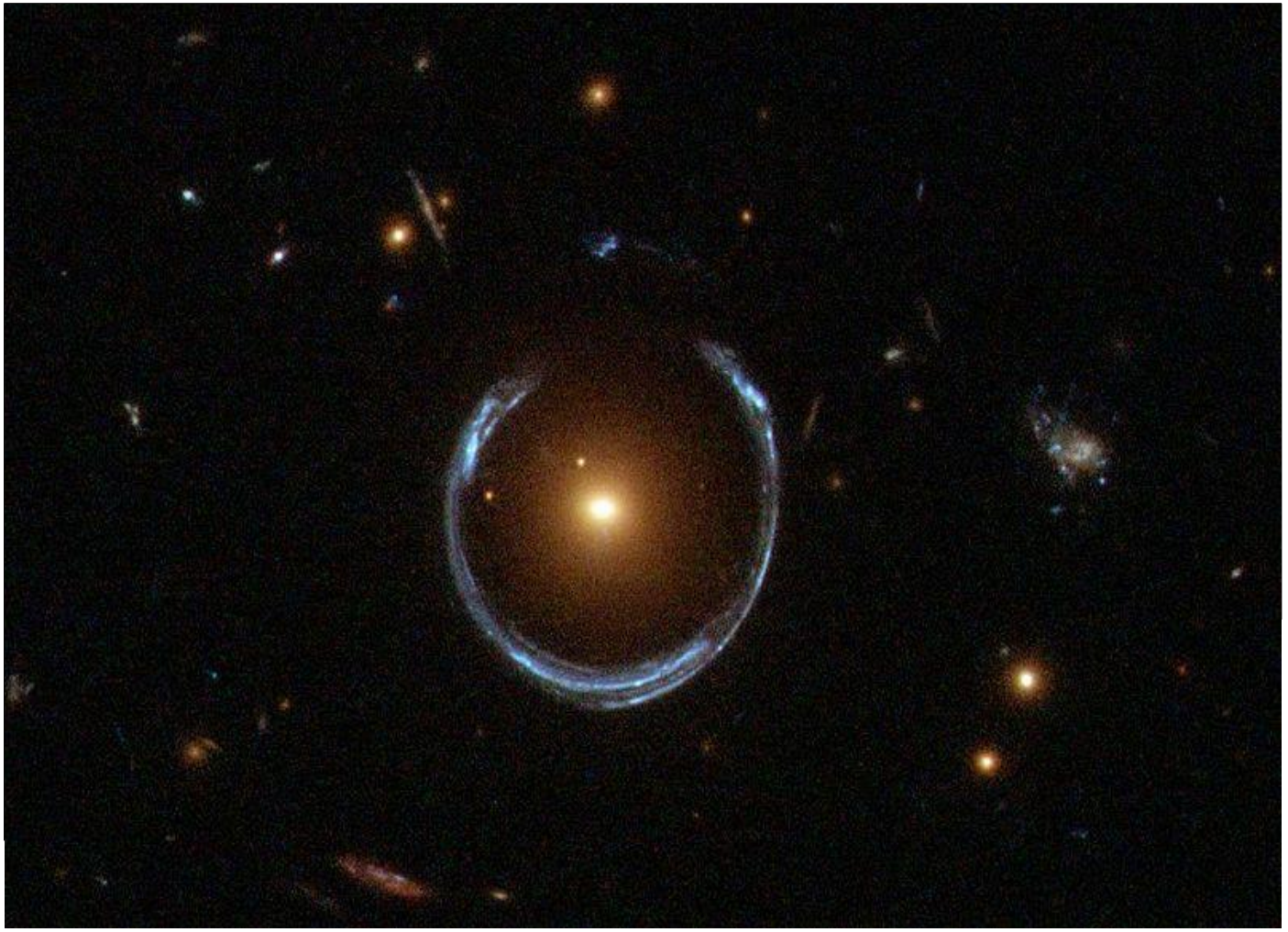
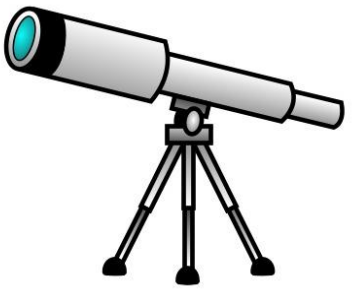
Depending on configuration, can form an "Einstein Ring" (---> spectacular images!)





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Playing with GravLens3

Original image

Debbie Bard of SLAC

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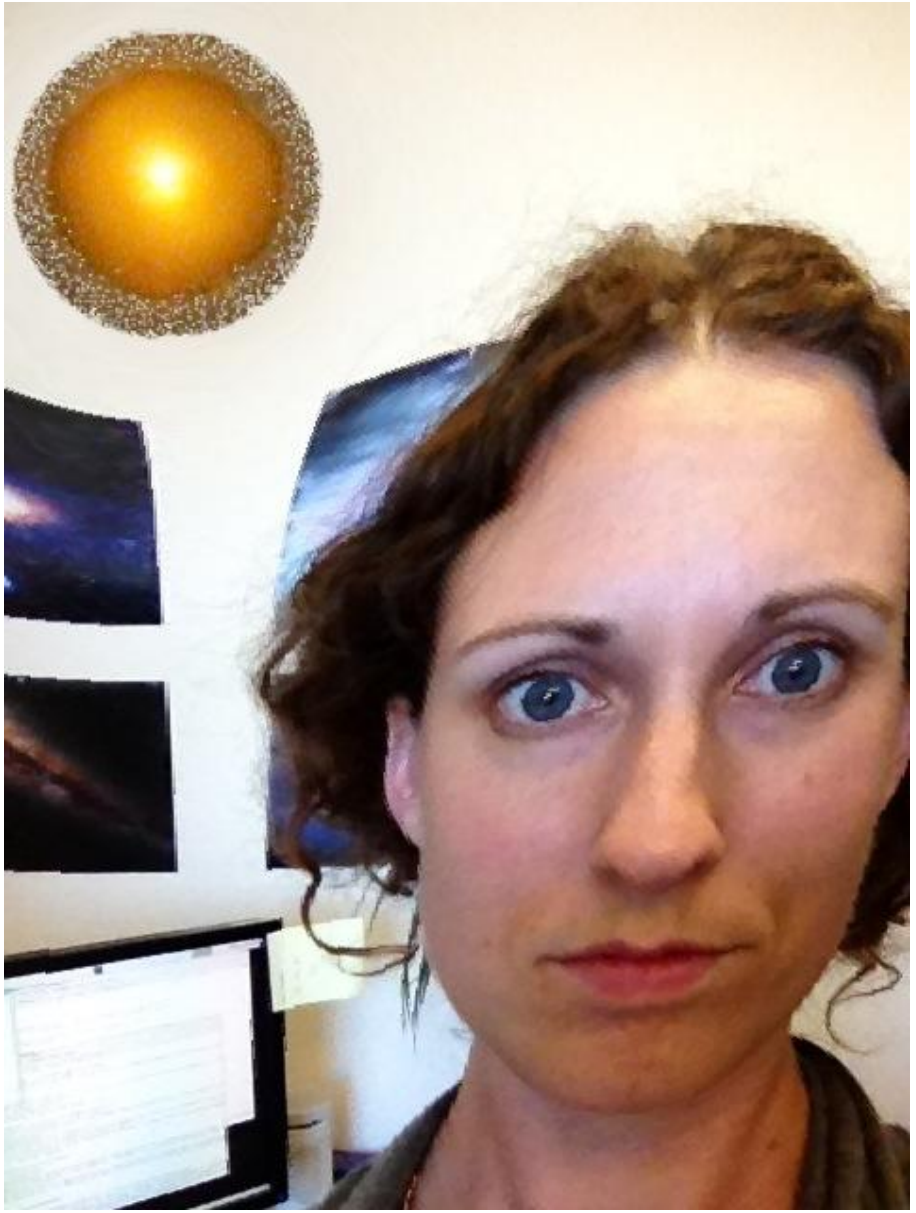
GravLens3 app
by Eli Rykoff
Free at the iTunes store!

Gravity *lenses*... Debbie!
(Distortion when lens is to the side front of source)

Lens radially distant from Source

---> Slightly distorted image!



GravLens3 app
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Distortion when lens is in front of source

Very distorted image!

GravLens3 app
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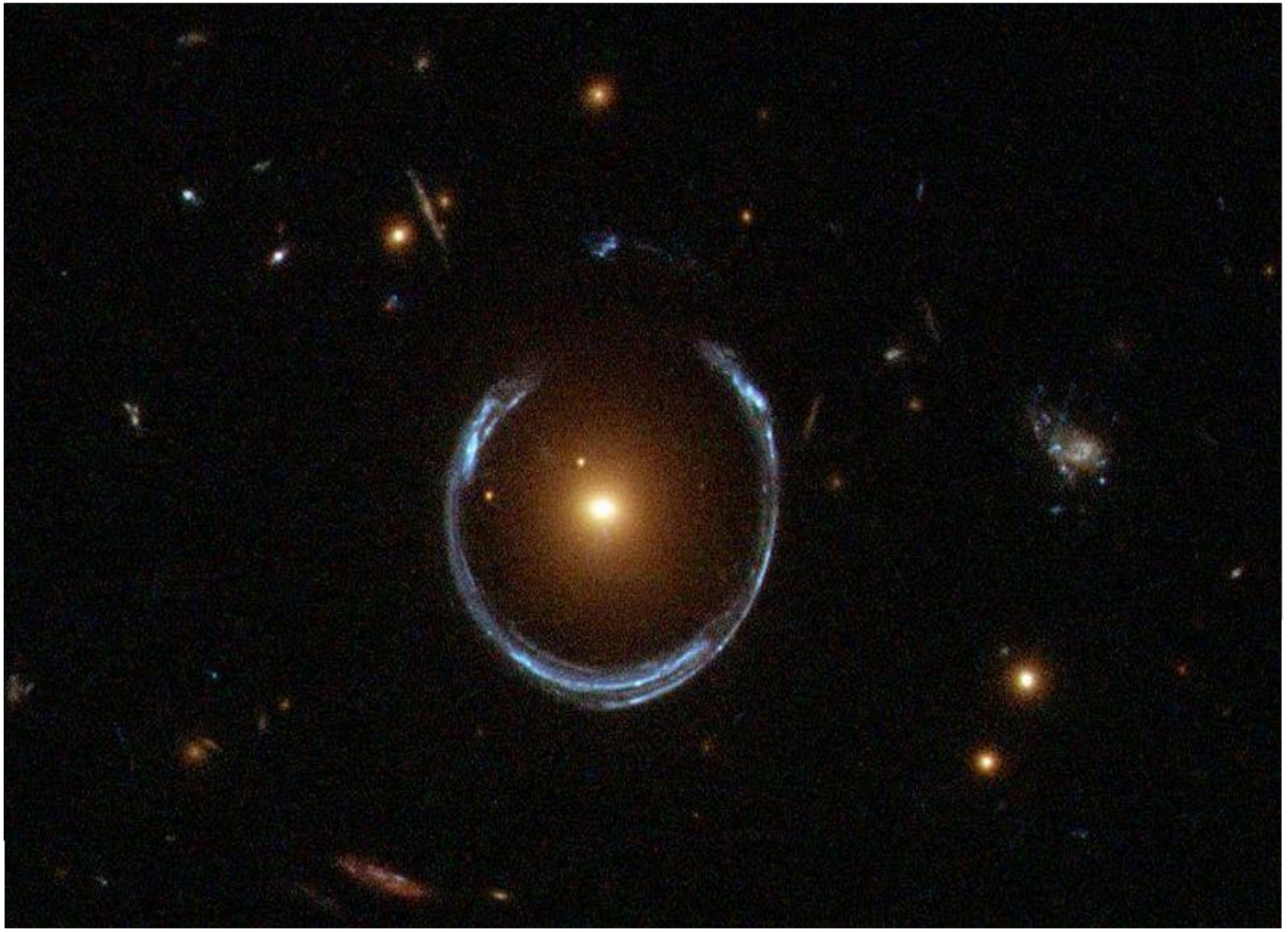
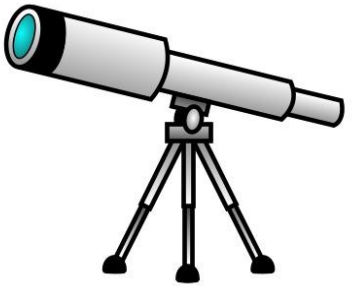
An Einstein Ring ...and an “Einstein Eye”





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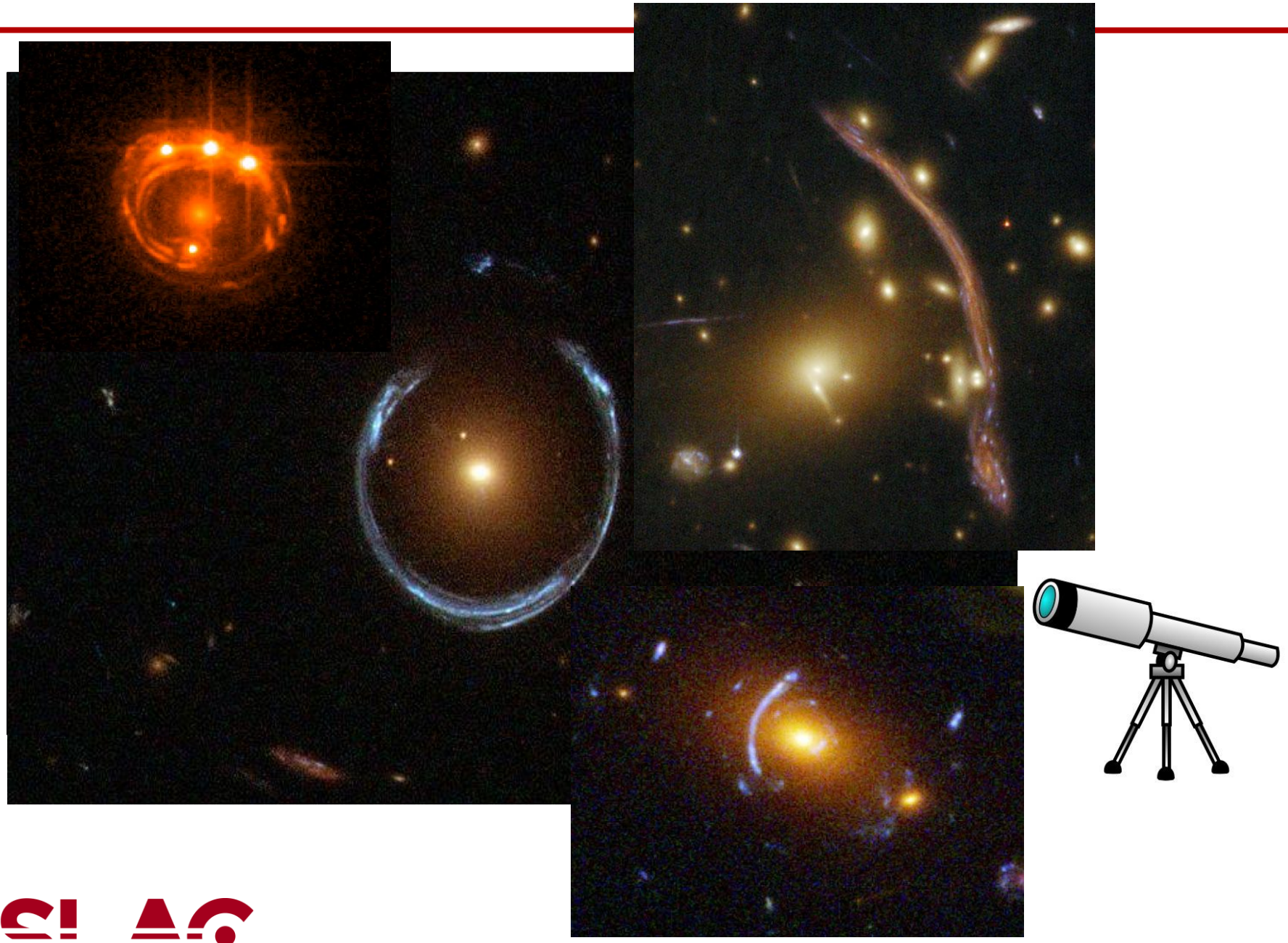
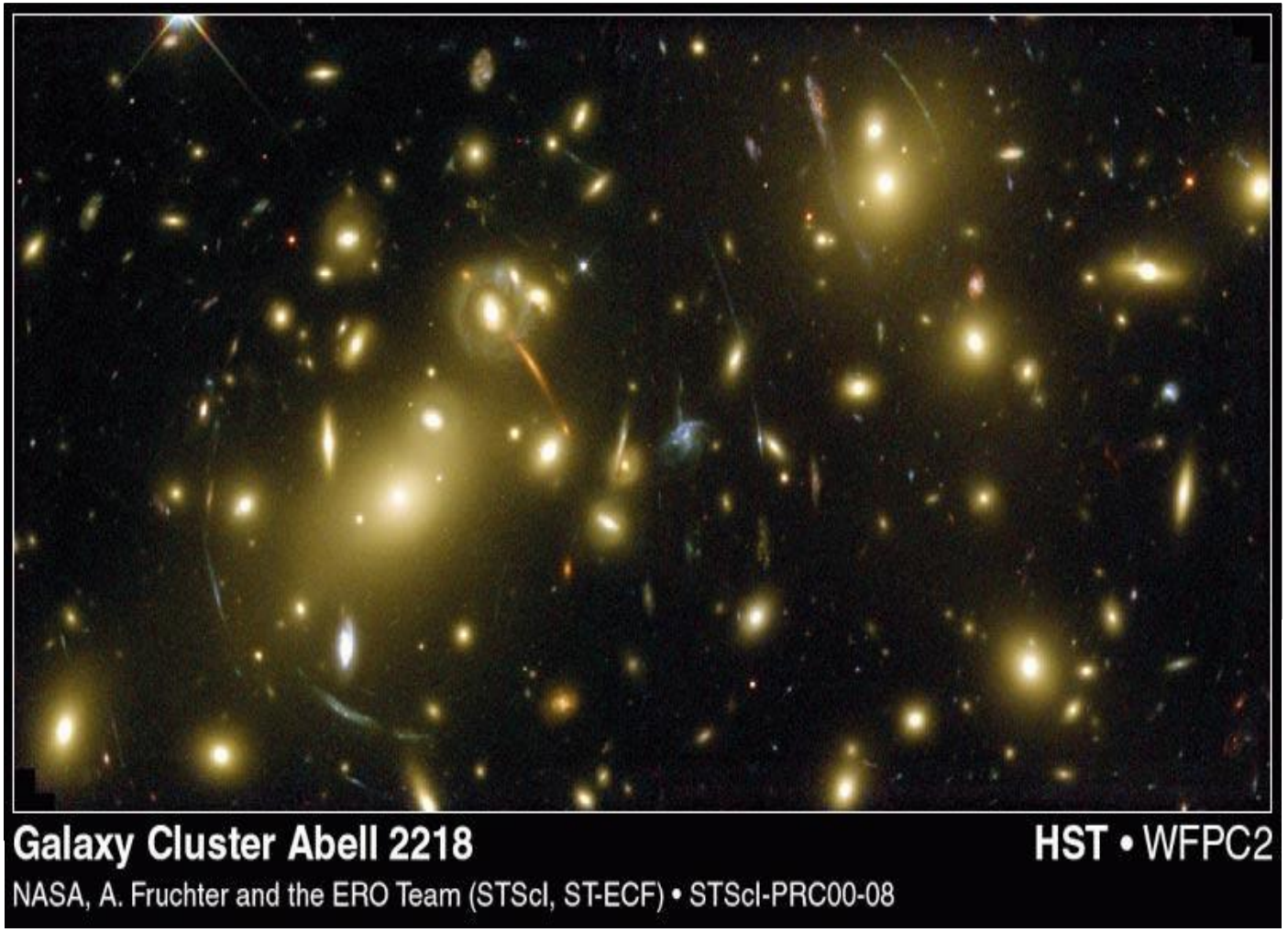
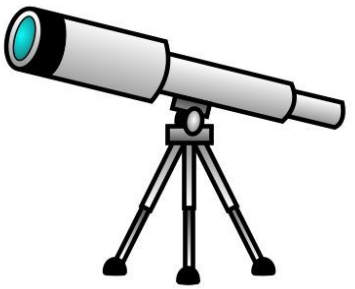
And: Einstein Arcs



A lot of mass (galaxy cluster)
→ A whole lot of lensing





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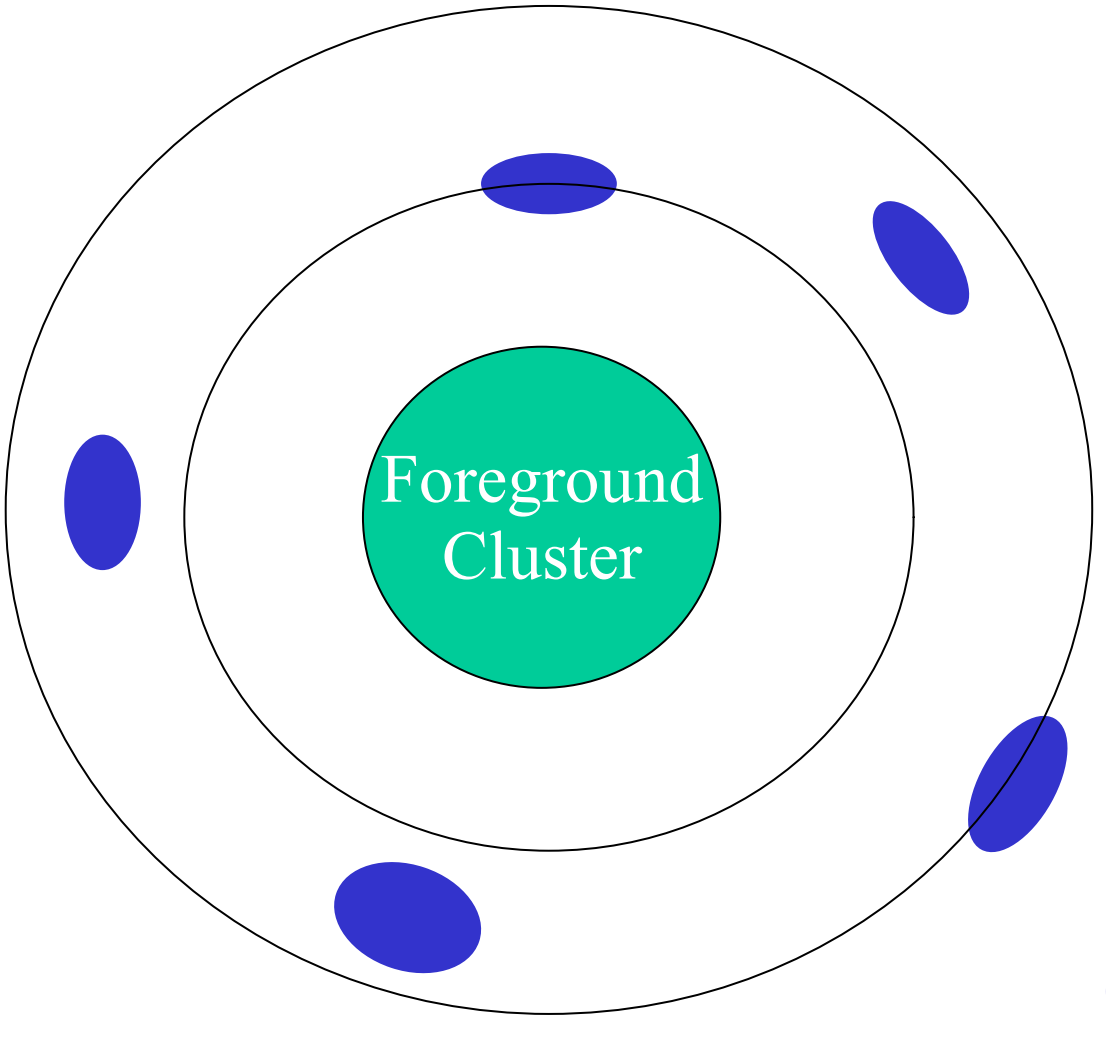
Lensing Effect on Background Galaxies



Note: the effect has been greatly exaggerated here

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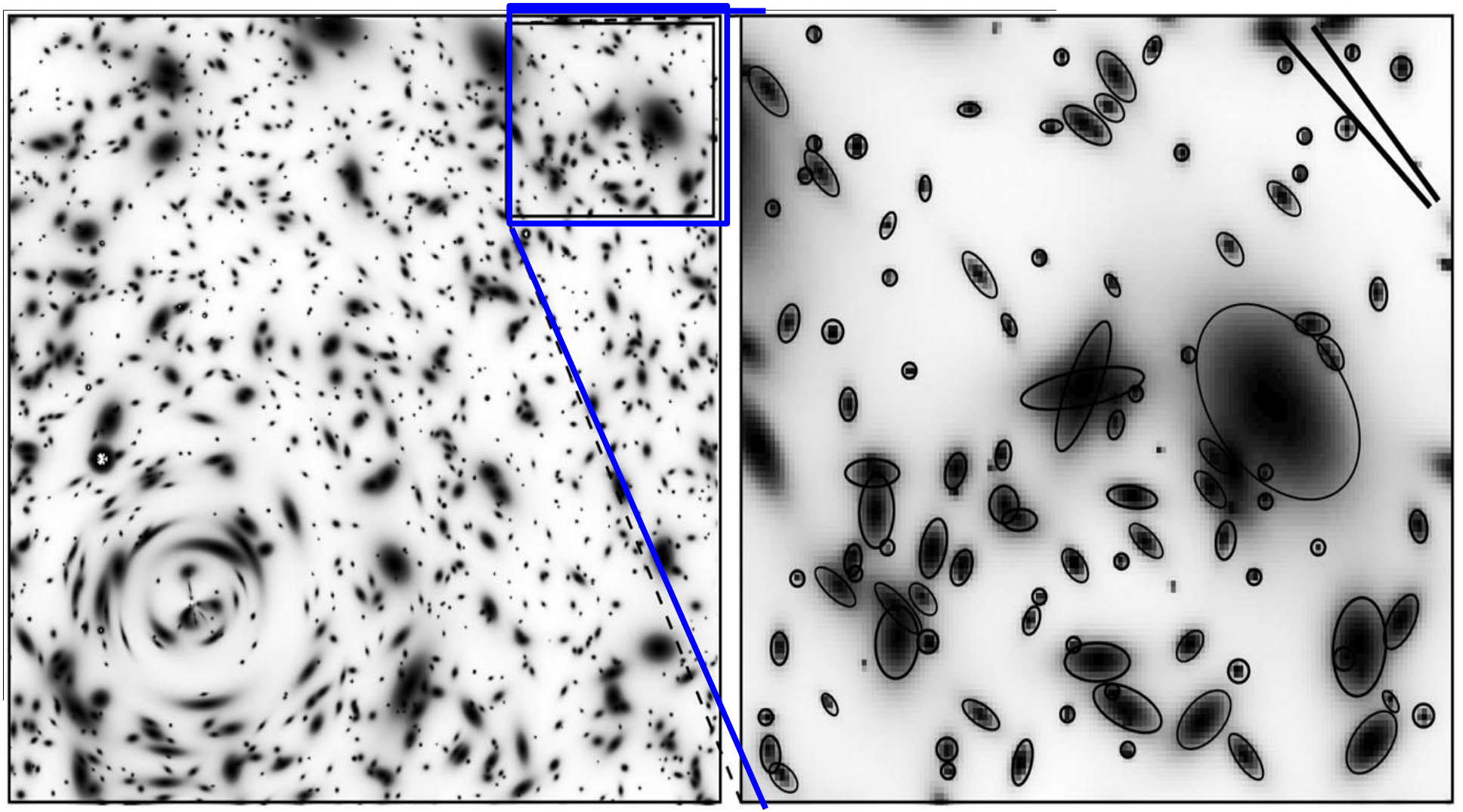
However: 'low level' lensing is not always obvious to the eye...



Simulation: Tyson et al.

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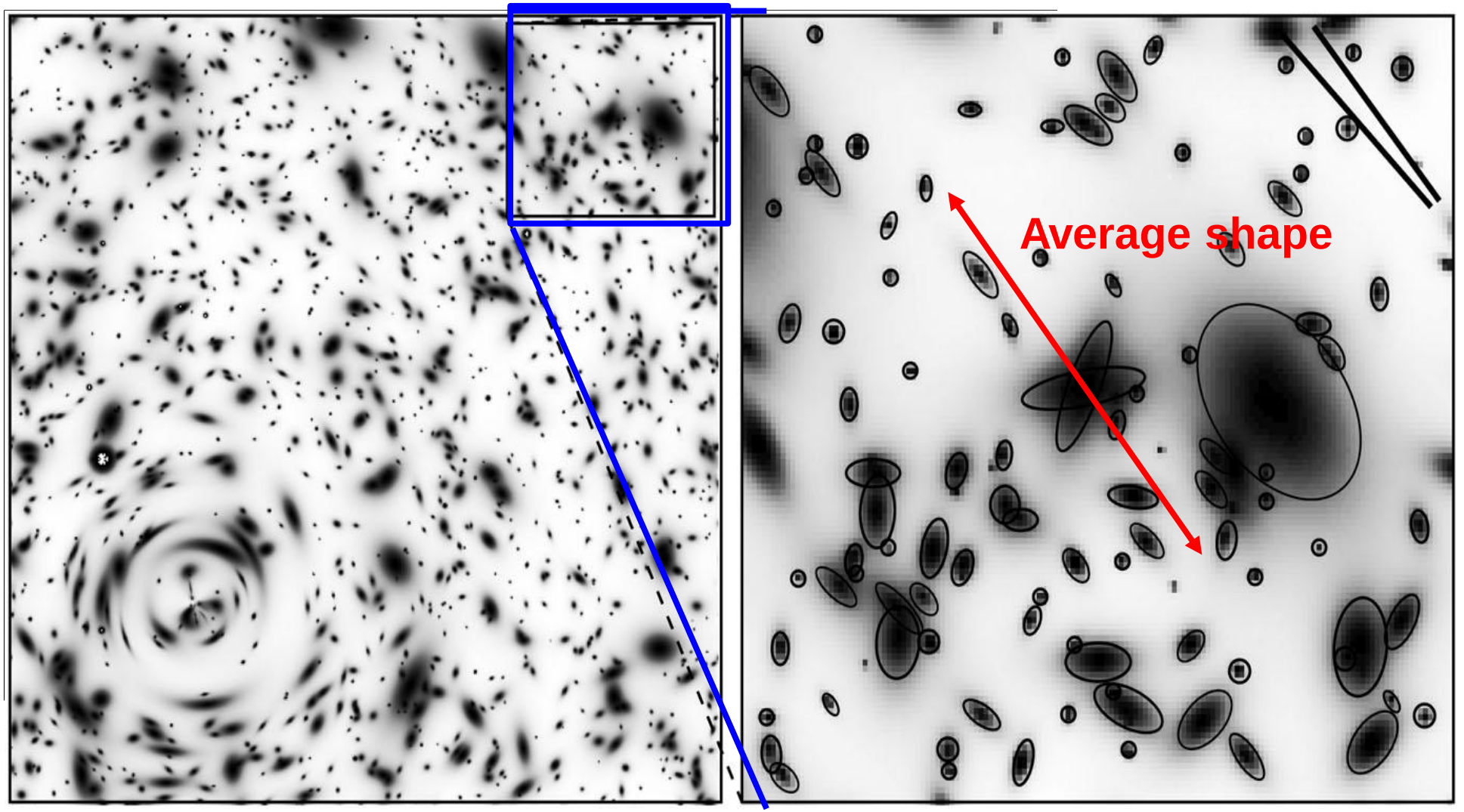
But *when averaged*, it can be picked out



Simulation: Tyson et al.

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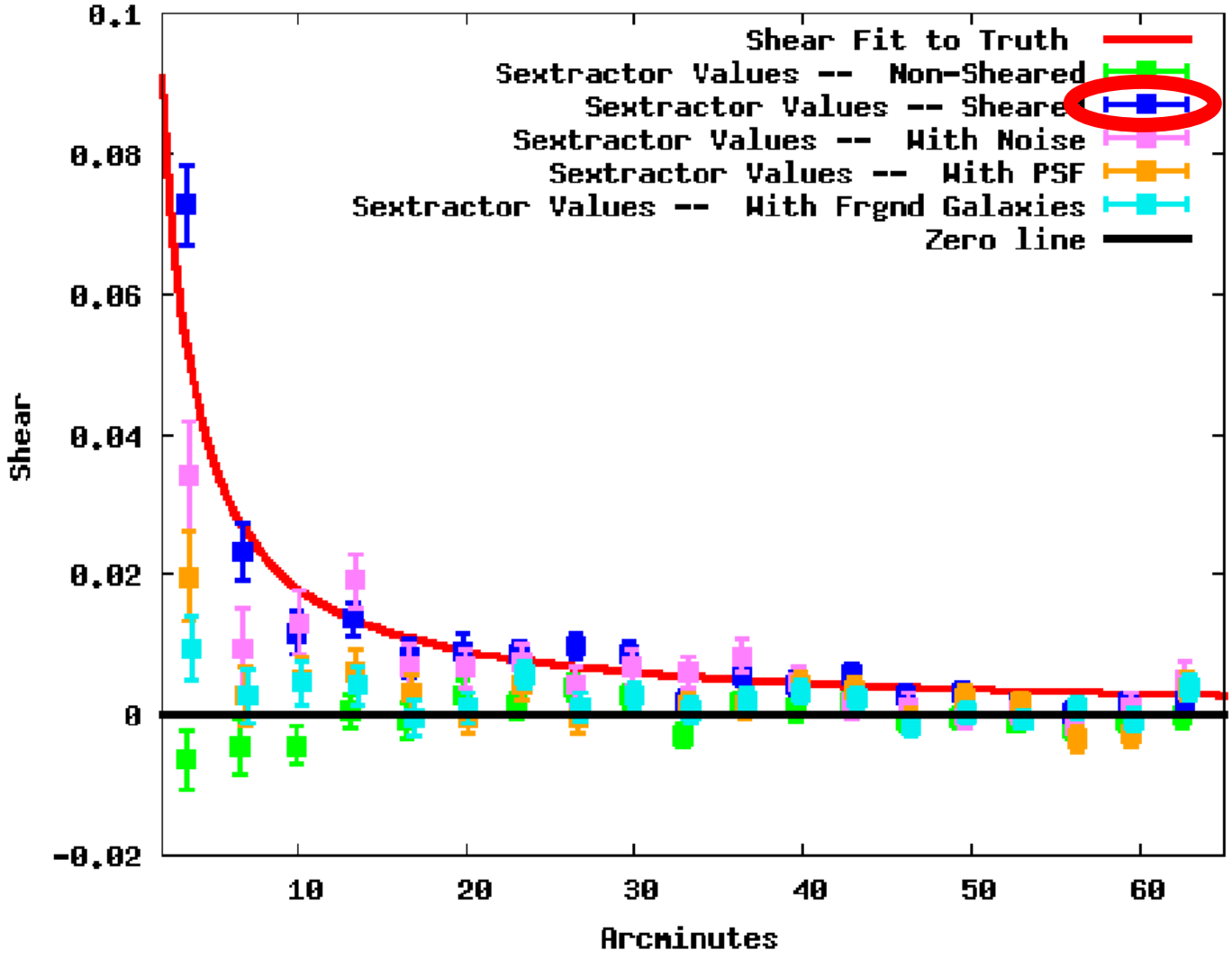
Lensing going out from lens center



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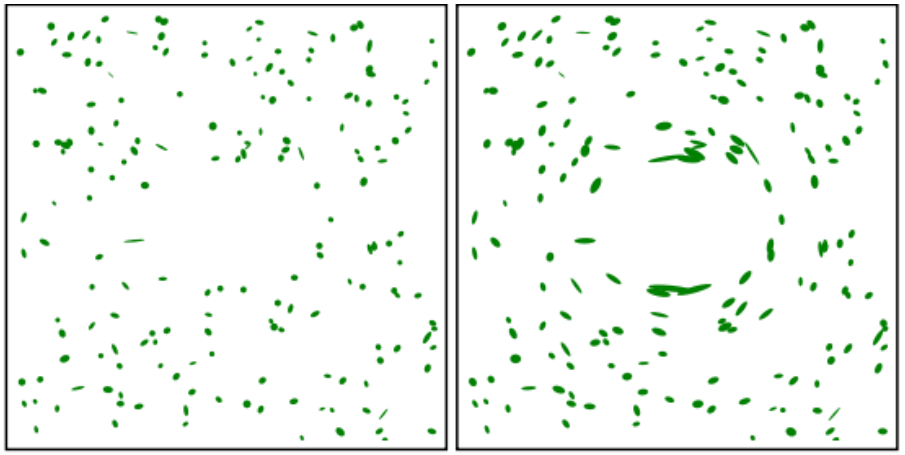
Dark matter and lensing

Reconstructing the lens

- Gravity lenses light → all massive objects lens
  - Stars, galaxies, galaxy clusters... all are mass lenses!
- We can use the lensed image of distant galaxies to reconstruct the mass of the ***lens itself***



No lensing **Lensing**

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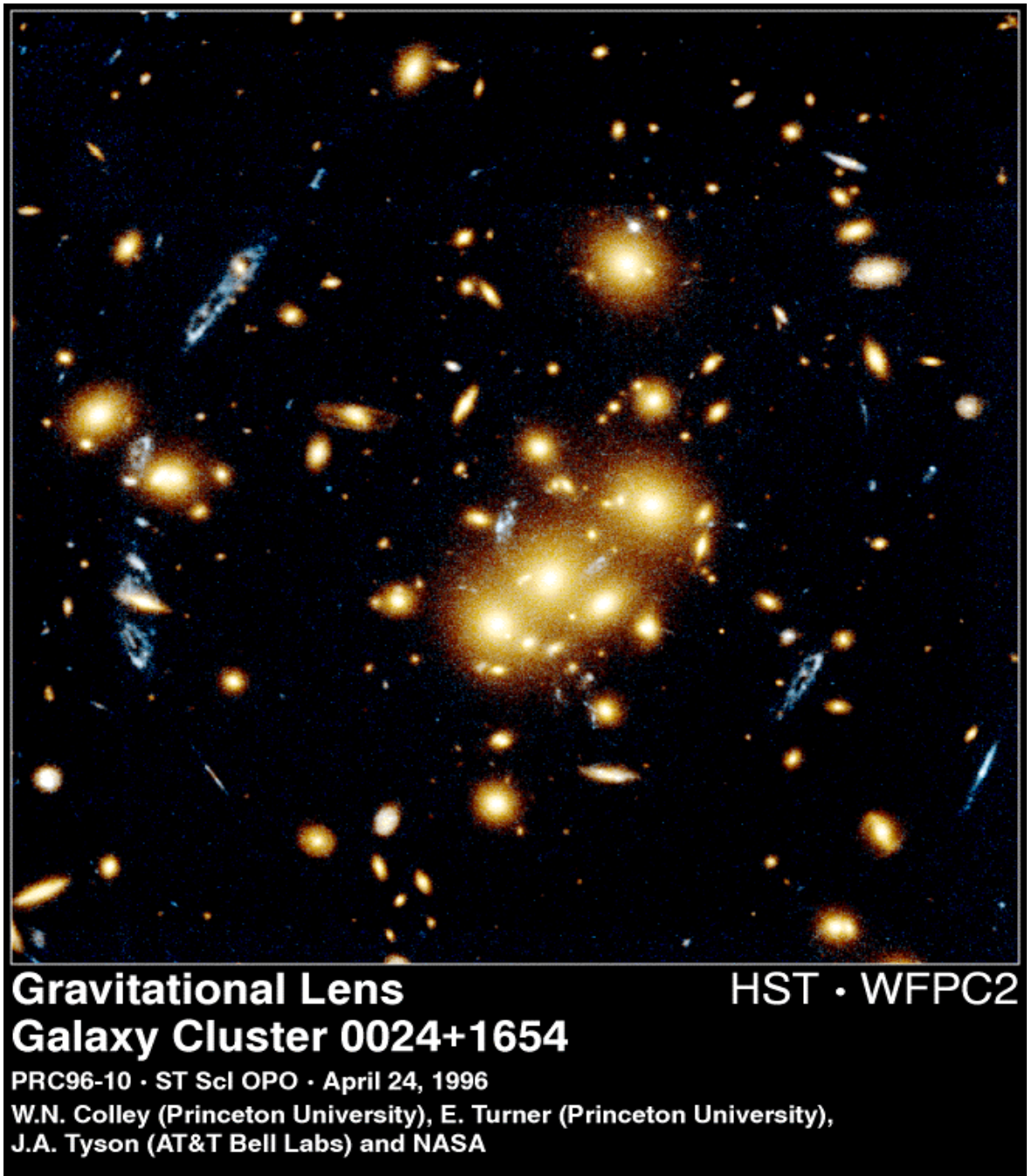
Reconstructing the lens

- From a Hubble image of cluster of galaxies.
- We want to figure out how much mass there is in this cluster...



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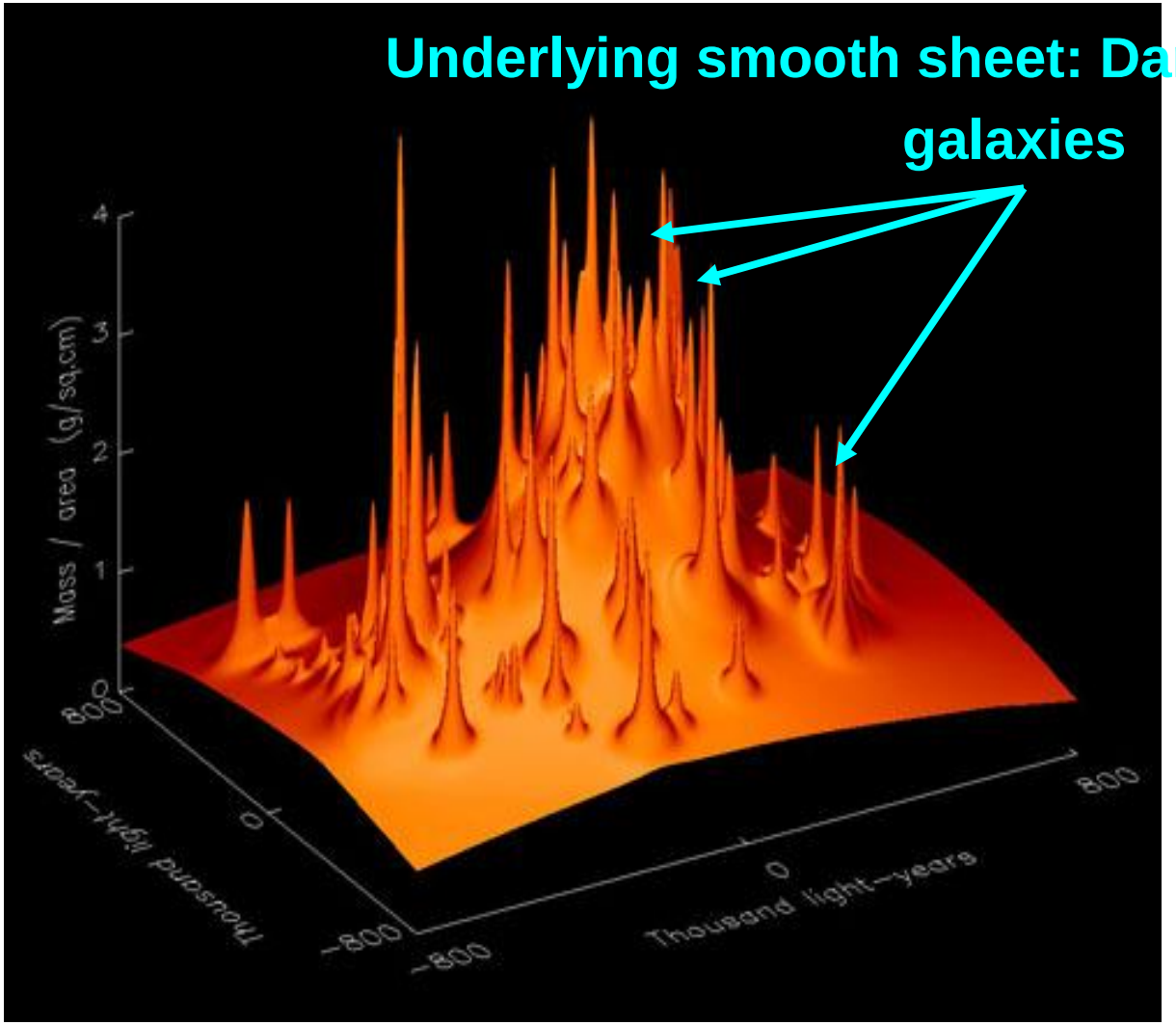
Reconstructing the lens

- Hubble image of cluster of galaxies.
- We want to figure out how much mass is in this cluster...
- Reconstruct lensing mass, based on distortion images of background galaxies!



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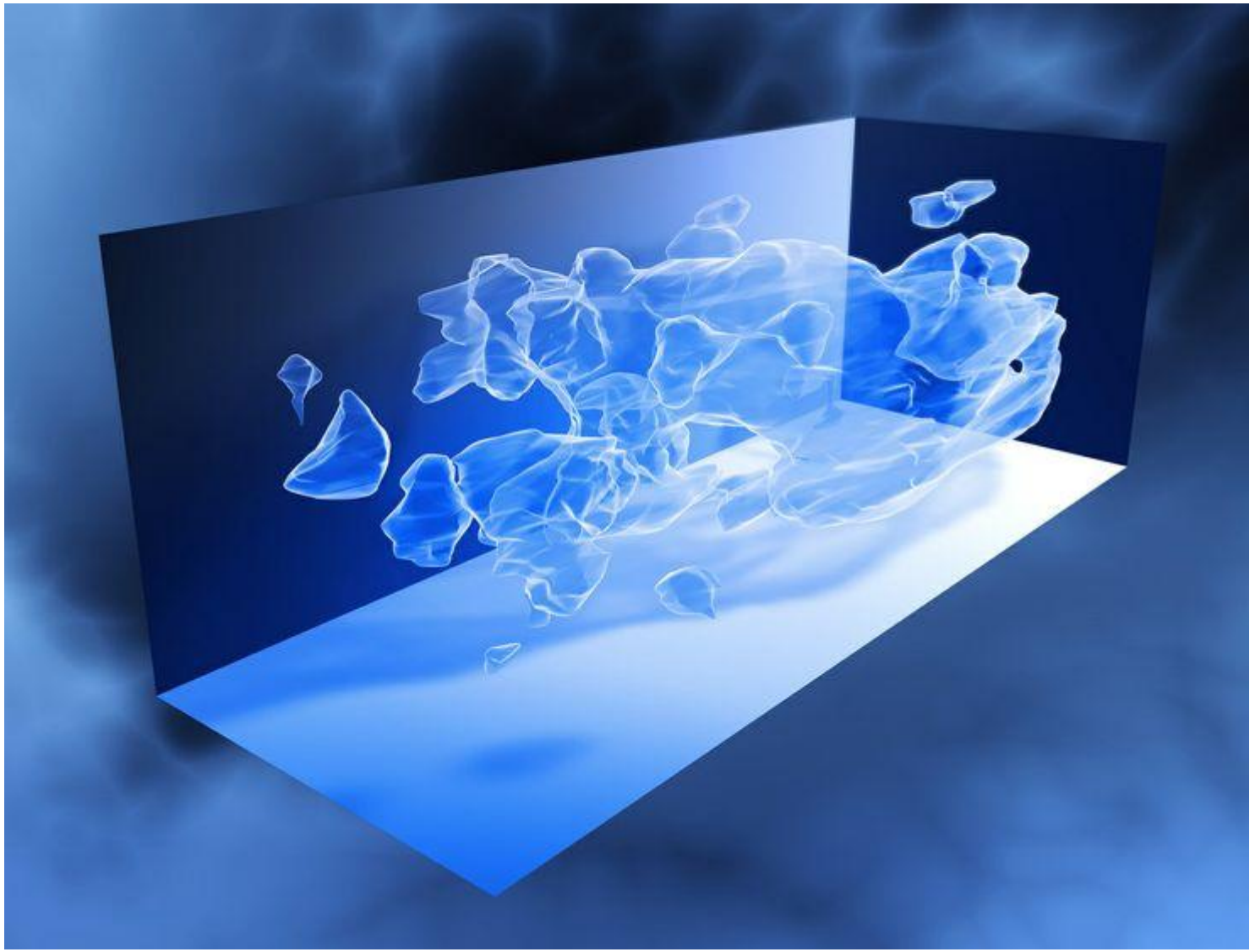
Mass Map of a Part of Universe from Lensing



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(COSMOS Team, 2008)

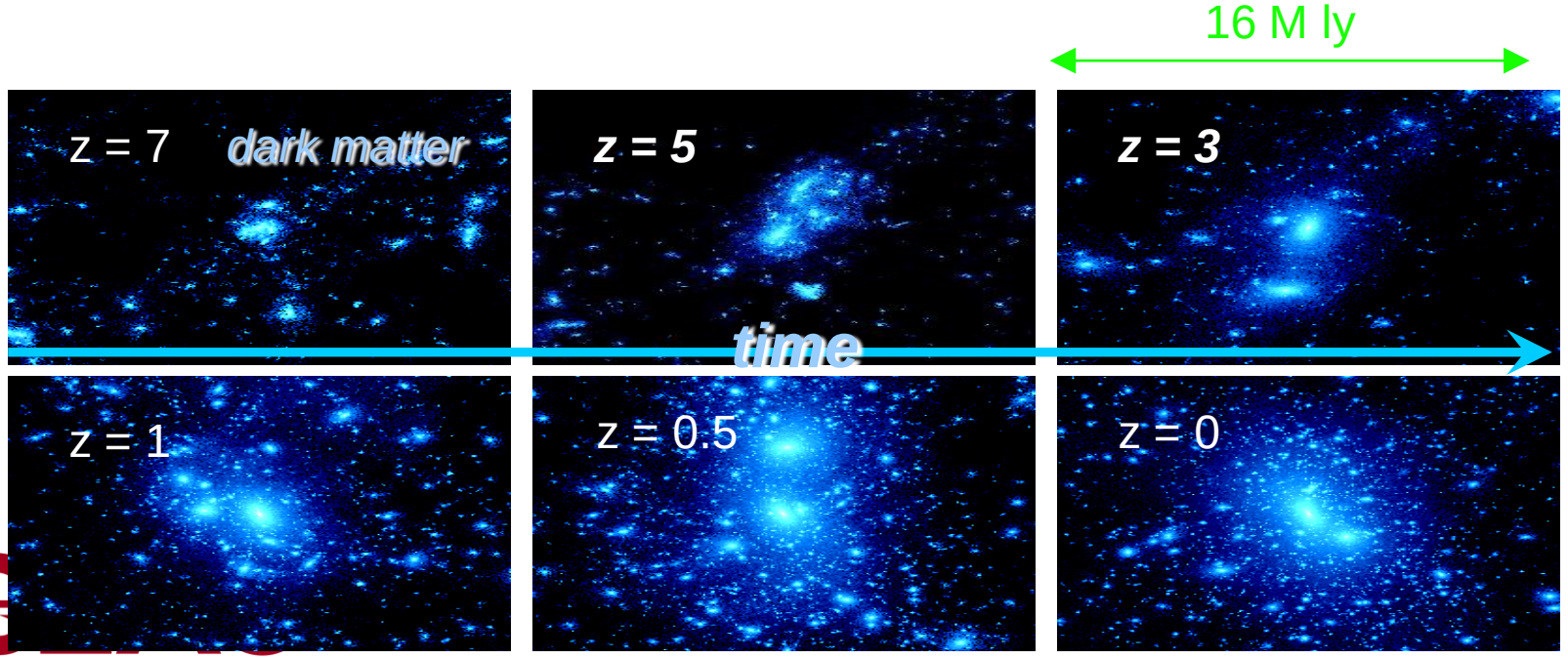

Dark energy and lensing

Galaxy Cluster Growth in Cosmic Time

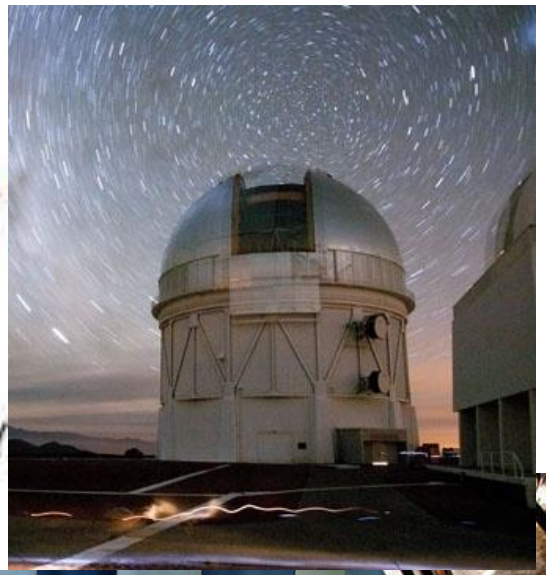
Dark Energy opposes galaxy cluster collapse

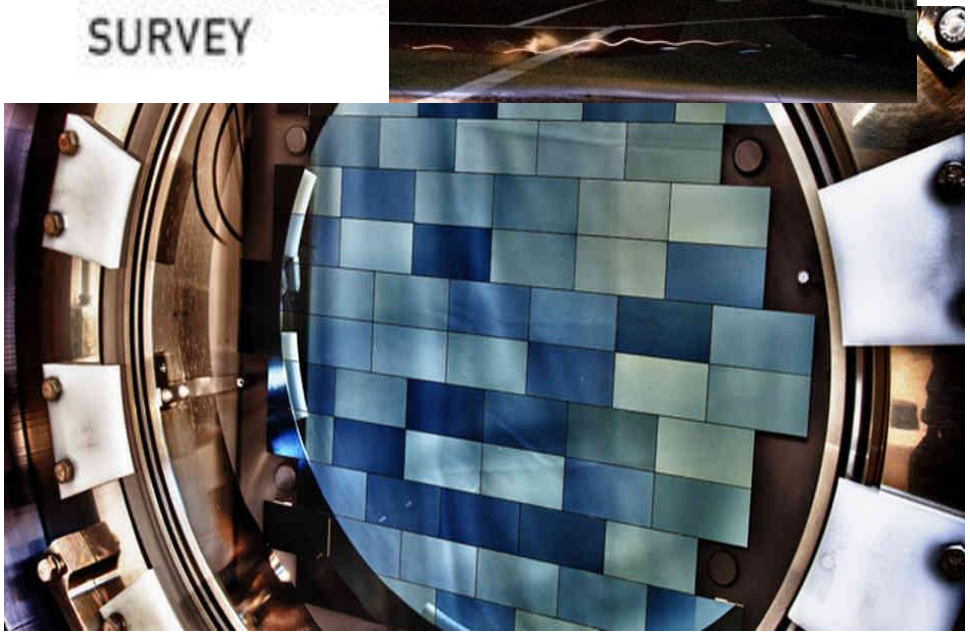
Thus we can learn about Λ using

mass of clusters as a function of z = redshift (z=0 is now, higher z is farther back in time)



Gravitational Lensing and SLAC





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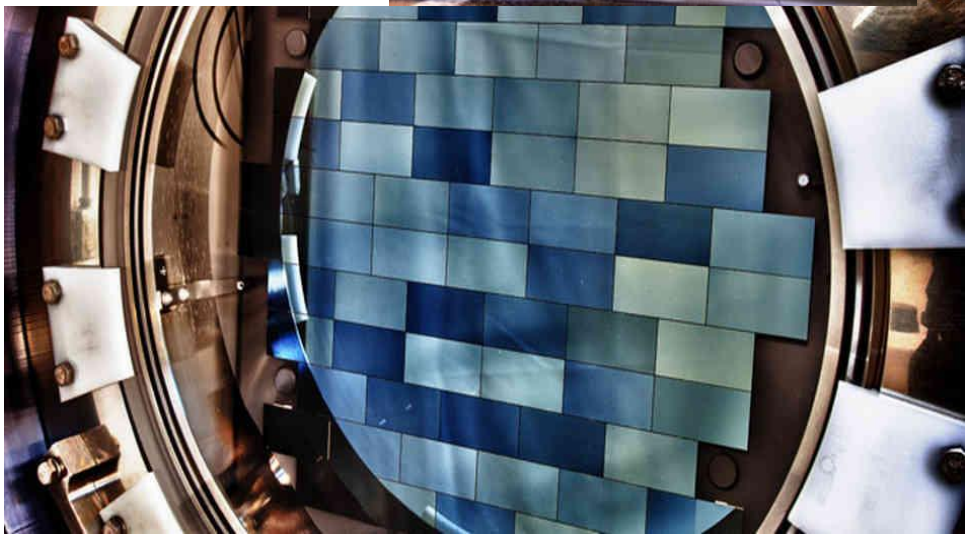
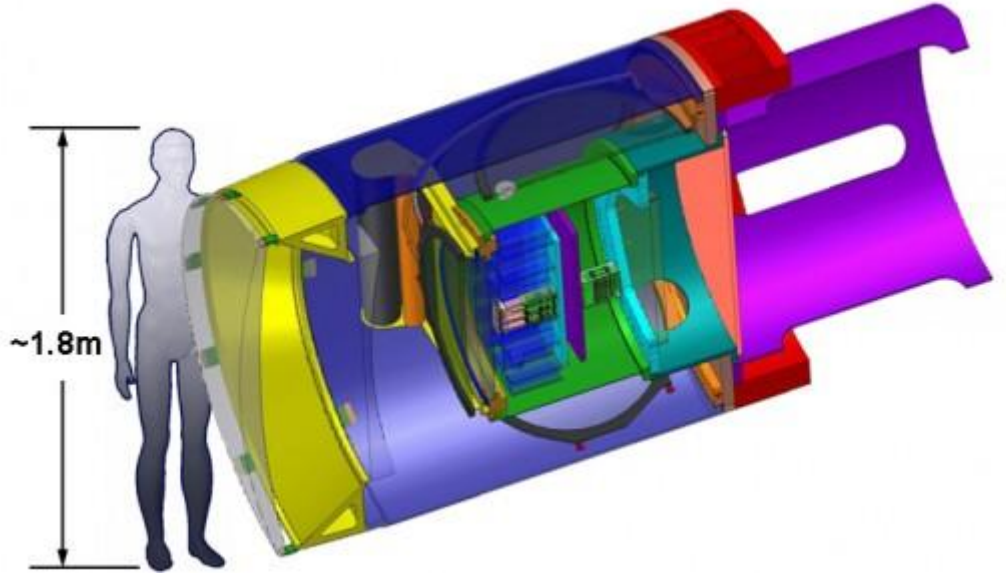
Gravitational Lensing and SLAC

DARK ENERGY SURVEY





LSST
Large Synoptic Survey Telescope

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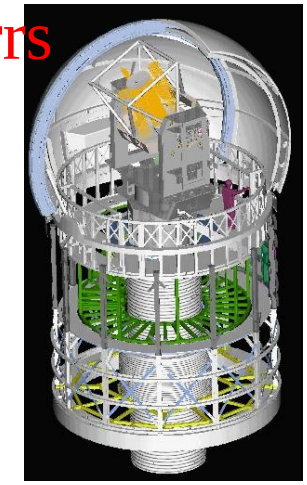
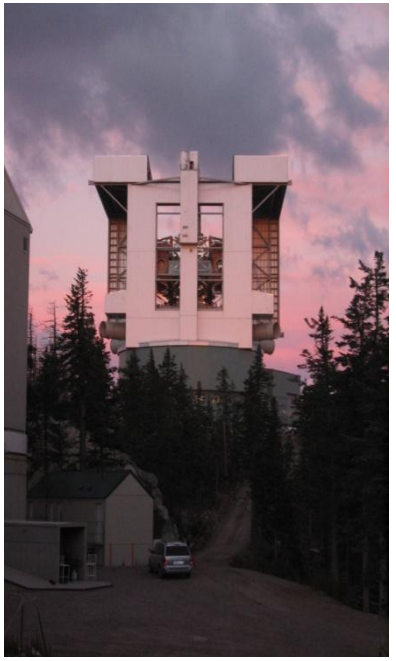
Several Upcoming Lensing Surveys

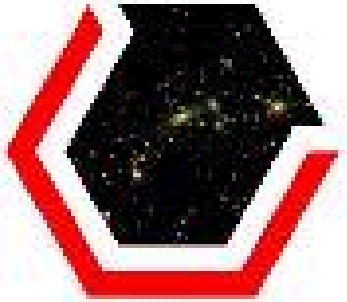
Panstarrs



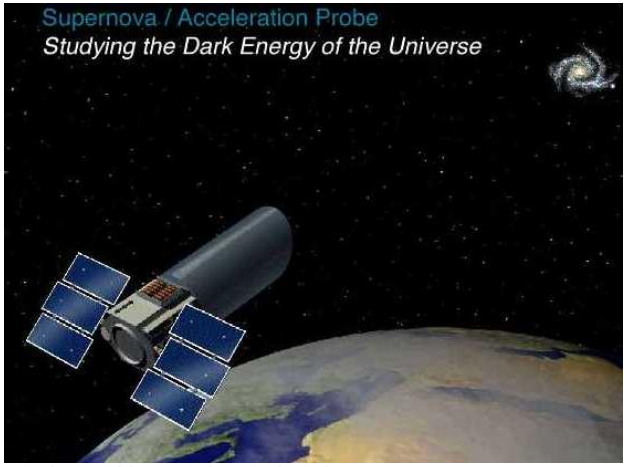
LBT-OWLS



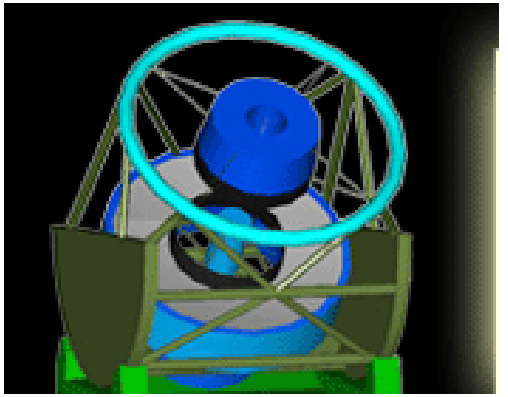
Dark Energy Survey



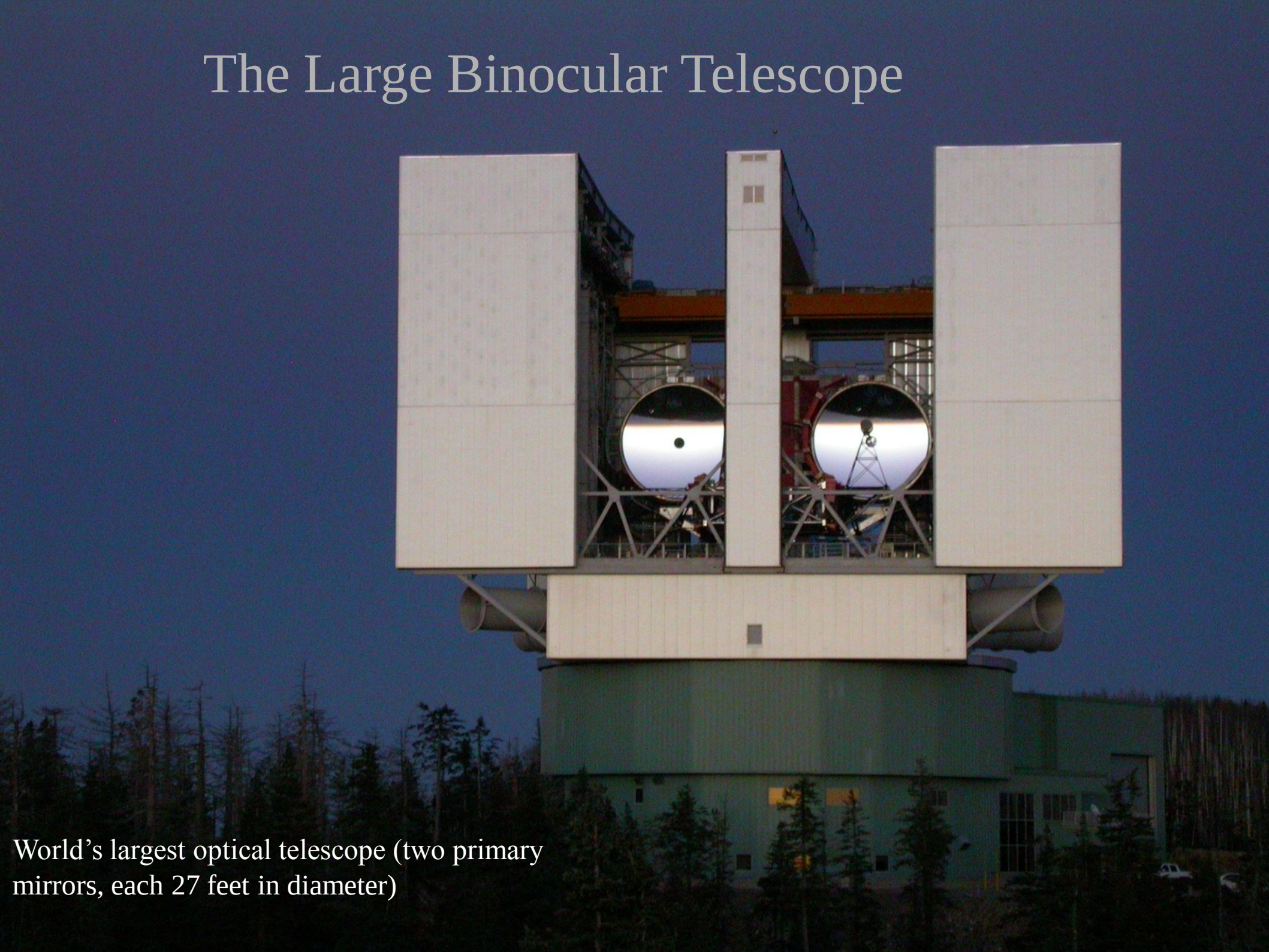
SNAP



LSST



The Large Binocular Telescope



World’s largest optical telescope (two primary mirrors, each 27 feet in diameter)

Summary (1/2)

- Lensing is an amazing probe of matter in the universe.
- Galaxy clusters give some of the strongest evidence for dark matter.
- Lensing can constrain theories of dark energy.

Summary (2/2)

- Dark Energy Survey and Large Synoptic Survey Telescope allow us to probe deeper than ever before.

- And, on the interactive side...

Some things to play with...

-  GravLens3 (Eli Rykoff)
  - Free app on the iTunes store

- spacewarps.org (Phil Marshall)
  - Crowd-sourcing strong lens identification

Finally: How a Cosmic Perspective Can be valuable to us in our Lives

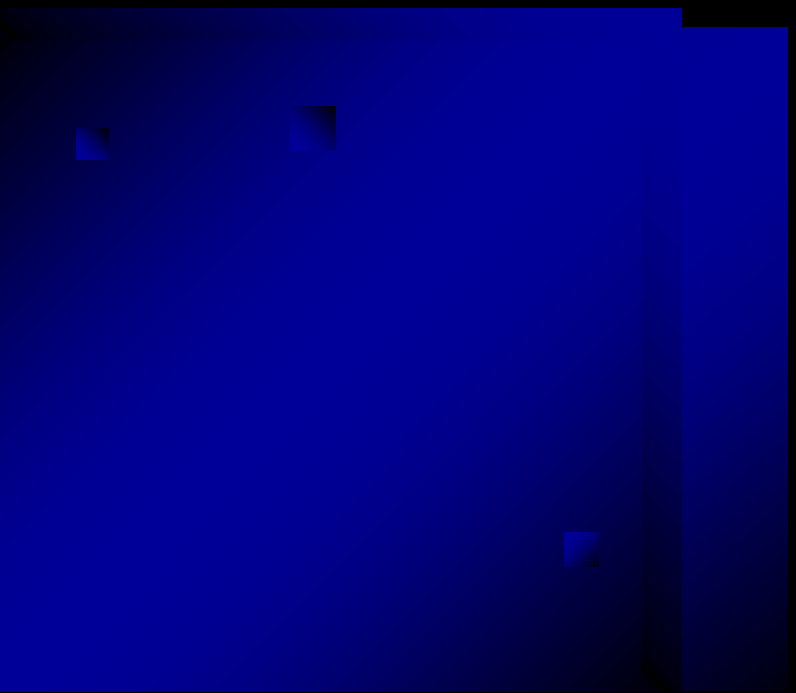
To my mind, there is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world. To me, it underscores our responsibility to deal more kindly and compassionately with one another and to preserve and cherish that pale blue dot, the only home we've ever known.

Carl Sagan, May 1996

See more at: http://www.skyimagelab.com/pale-blue-dot.html#sthash.zkPOhAkx.dpuf

I maintain that the cosmic religious feeling is the strongest and noblest motive for scientific research – A. Einstein, NYT Magazine, 1930

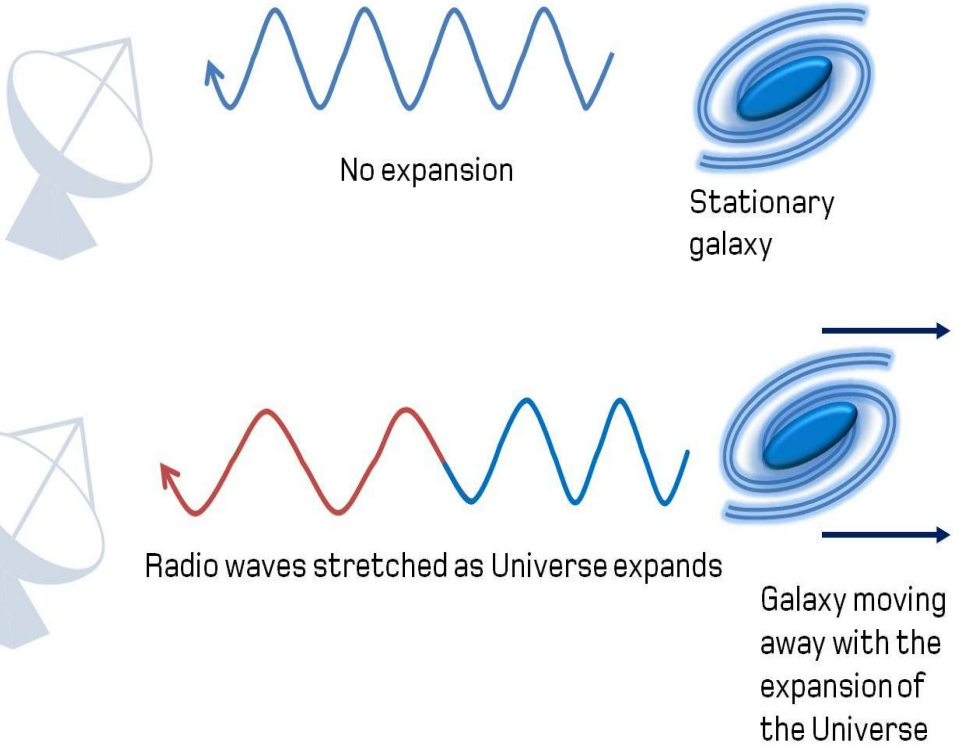
Backup Slides



Gravitational lensing: magnification

The Universe is expanding

- Redshift: like Doppler effect, but with light.
- Light from objects moving away from us appears more red.
- Universe is expanding → more distant objects appear more red to us.



A Very Quick History of Particle Physics

1869 Periodic table finalized – all elements fit

1897 e- = electron (UK)

1910's proton (UK etc.)

1932 neutron (UK)

By 1932: tidy picture of three basic particles explained everything in the Universe

1932 e+ = positron (cosmic rays -- CA)

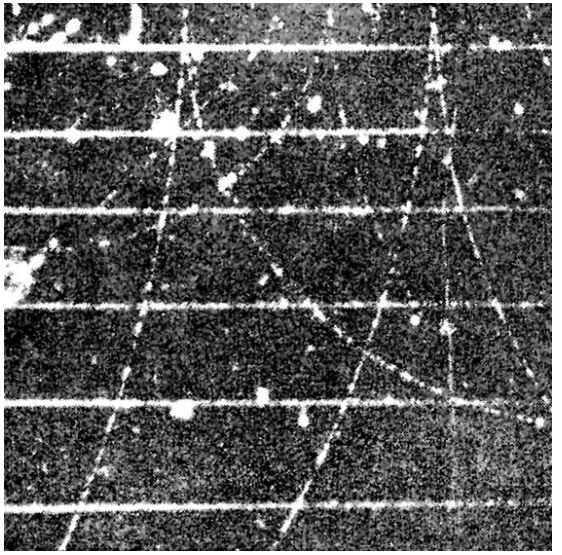
1936 μ – (c. rays – CO and Panama)

1947 π (c. rays – France and Bolivia)

1947 Kaon (c. rays – Mt. Wilson, CA)

1947 Lambda (c. rays – UK)

Then: many, many more…



http://nssdc.gsfc.nasa.gov/image/astro/hst_ngc3314_0014.jpg

http://www.physicscentral.com/action/2000/images/antimatter-img2.jpg

Finally: the ``congealing" of the SM (The **Standard Model**)

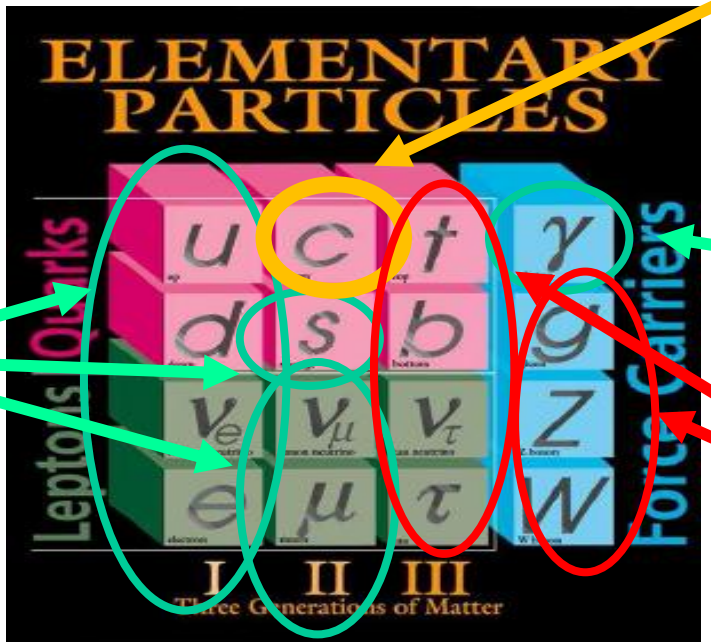
Late 60's: Electroweak theory combines electromagnetism and weak nuclear force

Then: quarks + gluons = nuclear physics ironed out

1970's-1990's: all other predicted SM particles tracked down (heavier quarks and leptons, more force carriers)

All new matter particles fit as an extra generation into the already existing theory

"November Revolution" of 1974



Also known by late 60's

Known by late 60's

Found 70's-90's

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Putting together the building blocks

Anything made of quarks is a *Hadron*

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.

These are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons

These are a few of the many types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

How to make up hadrons from quarks

Now we see it's back to being simple! (relatively.. ☺)

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